Project FALCON

Dynamic Asset Rating Overhead Lines

September 2015

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FALCON

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Executive summary

With the growth in all types of low carbon generation, such as wind and solar photovoltaic (PV), and the introduction of new demand technologies such as electric vehicles (EVs) and heat pumps, Western Power Distribution's (WPD) electricity network is expected to see unprecedented swings between peaks and troughs of energy usage in localised areas.

WPD's Project FALCON has examined a range of innovative alternatives to conventional reinforcement that might be used to mitigate the impact of such energy usage. This was undertaken firstly through physically trialling four engineering and two commercial techniques. Secondly, innovative alternatives where examined through building and operating a software tool. This tool: models the real network under a range of energy use scenarios out to 2050; identifies network constraints that arise over time; employ the studied techniques to mitigate constraints; and assesses impact and benefit.

This report is one of a series describing the engineering technique trials, and focuses on Dynamic Asset Rating (DAR) of overhead lines (OHL) within networks. DAR is the process of using prevailing weather conditions to run an asset at a rating potentially higher than its name plate to take advantage of for example, cold temperatures. Within the project, dynamic ratings were considered as an alternative to conventional reinforcement, the traditional engineering remedy to network constraints.

Recommendations resulting from this report are;

Whilst it has been demonstrated that ampacity of 11kV OHLs can be assessed, improvements in ampacity are essentially dependant on wind speed/direction, and cannot be relied upon if reasonable planning certainty of capacity is required. It is recommended that 11kV OHL DAR should not be considered a feasible technique for solving long term 11kV distribution network issues at this time. However, this observed ampacity benefit clearly does have operational benefit in specific contexts e.g. extending ratings of overhead lines associated with wind generation because the increased loading due to the output from the wind turbines will correlate with wind speed that could enable an increase to the line rating.

Key learning is as follows;

Overhead line DAR is dependent on thermal models. Models were prepared under this project and good correlation was found between measured and calculated line temperature.

The technique trial identified significant average real time ampacity benefits. However, the ampacity varies over a large range within a very short time frame largely driven by variation in wind speed. This rapid variation in wind speed coupled with low thermal mass of the asset/ short time constants for changes in temperature means that the asset cannot be loaded and relied upon at these identified enhanced average levels for extended periods of time due to the potential for changes in weather conditions.

The potential for this rapid fluctuation in ampacity led the project to investigate the possibility of using forecast weather to estimate forward ampacity (on a day ahead and week ahead basis). This investigation was conducted to address the issue that modelled ampacity indicates an “of the moment” ampacity but does not address the question of capability of the asset over a forthcoming period e.g. day ahead/week ahead.

The method of estimating forward ampacity within this project, concluded that the calculated forward ampacities tended towards the pre-existing static ratings as due account was taken of uncertainties in weather forecasts.

It is worth noting that comparisons between “of the moment” dynamic asset rating and static ratings for September 2014 suggests that the static rating of this month might be better treated as a summer period rather than an autumn period. Clearly this is based on the evidence of only one September period. It is recommended that this data is reported and examined in line with ENA ER P27.

SECTION 1

Project Introduction[1]

[1] This introduction to Project FALCON (Flexible Approaches for Low Carbon Optimised Networks) is common to all the engineering technique Final Reports.

With the growth in all types of low carbon generation, such as wind and solar photovoltaic (PV), coupled with the introduction of new technologies such as electric vehicles (EVs) and heat pumps, Western Power Distribution's (WPD) electricity network is expected to see unprecedented swings between peaks and troughs of energy usage in localised areas. This expected change in nature of customer demand and electricity generation will have an impact on networks nationwide and globally, and provides a significant challenge to WPD, and all electricity network operators.

Part of WPDs approach to this challenge has been look at new flexible ways to design, optimise and manage the network into the future. Project FALCON (Flexible Approaches for Low Carbon Optimised Networks) is designed to help answer these questions and is focussed on the Milton Keynes area 11kV network.

In the past network operators have used conventional reinforcement to deal with constraints but it can sometimes be over engineered to meet only peak demands; it can also be expensive, disruptive and inefficient. In project FALCON, WPD and its partners are trialling alternative techniques and will assess if they are more flexible, cost effective, quicker to deploy and more effective at managing these new demand requirements than conventional reinforcement. The techniques are:

- Dynamic Asset Ratings – Using prevailing weather conditions to run an asset at a rating potentially higher than its name plate to take advantage of for example, cold temperatures.
- Automatic load transfer – load is redistributed between 11kV feeders.
- Implementation and operation of a meshed (interconnected) 11kV network.
- Deployment of new battery technologies allow the flow of power on the network to be changed as the battery is charged or discharged.
- Demand Response services - the use of localised smaller generation and load reduction services that can be provided in the event of a local constraint.

Central to the project is the Scenario Investment Model (SIM) - a new piece of software being developed to assist long term network planning. The SIM performs load flow analysis for the network for 48 half-hourly periods during the day for different days of the week and different seasons of the year. Predicted load patterns extend as far as 2050. A network planner will operate the SIM to help with planning based on load forecasting. When a network planner is running the SIM and a voltage or thermal problem is found, the SIM will select the techniques that could help resolve the problem and determine how they could be applied to the network. The best solution can be selected using a weighted metric that combines elements such as installation and operating costs, network performance, losses and disruption to customers.

This report presents the work undertaken through project FALCON on the dynamic asset rating of Overhead Lines on the 11kV network.

SECTION 2

Introduction to Technique Trial

2.1 Presentation of Learning

Throughout the document, key learning is presented in a box as follows:

LP #	Brief description of learning.

Each piece of trials feedback is referenced as a Learning Point (LP) with a unique number.

2.2 General Overview of Dynamic Asset Rating Technique

Traditionally overhead lines (OHL), transformers and cables have been assigned capacity ratings intended to ensure operation within safe operating limits, and allow assets to achieve nominal service life. These ratings may be fixed for specific periods of time (e.g. summer and winter ratings of OHLs), or may relate to a load that has a daily cyclic characteristic (e.g. transformer and cables). However, these ratings essentially do not take the current/present environmental conditions into account, nor do they take into account the current/present thermal state of the asset. In this respect, the ratings are regarded as “static” – not responsive to the current thermal or environmental conditions of the asset. These “static” ratings make assumptions about prevailing environmental conditions (air temperature, wind speed and direction etc.) and set a limit on electrical current passing through the asset such that safety and service life of the assets are maintained.

Dynamic Asset Rating (DAR) seeks to allow operation of these assets beyond the static limits, through dynamic assessment of the asset’s actual thermal state (derived from preceding operating circumstances), and the present environmental factors. Whilst seeking to increase capacity, this technique can also identify periods where the dynamic rating is calculated as less than the static rating, thereby potentially reducing the asset’s rating under some circumstances. The dynamic rating is often referred to as ‘ampacity’ – the maximum current that can pass through an asset before the temperature limits are reached.

This technique seeks to properly increase the capacity of assets during peak usage periods to alleviate constraints, whilst maintaining safety and managing impact on asset life. DAR can also be used to constrain flexible use of assets (e.g. generation) when environmental/load conditions are not favourable.

2.3 Overview of 11kV overhead line DAR technique

2.3.1 Background to static rating of overhead lines

The static ratings of OHLs have been calculated in ENA ER P27 [1] to ensure that conductor temperature, and therefore, conductor sag remains within set tolerances. To ensure public safety, estimates of seasonal weather have been used to set the static ratings. With the benefit of on-line weather monitoring, the dynamic rating, or ampacity (maximum current that can pass through a line before the temperature limits are reached) can be calculated.

The ratings of the OHLs are broken down into three seasons 'Spring/Autumn', 'Summer' and 'Winter 'and a prevailing ambient temperature is applied to each season. 'Spring/Autumn' rating has an ambient temperature of 9^0C and is from March to April and September to November respectively. 'Summer' rating has an ambient temperature of 20^oC and is indicated as being between May and August. 'Winter' rating has an ambient temperature of 2^oC is between December and February [2].

The 'Winter' and 'Spring/Autumn' ratings take into account the ability of the lines to carry larger currents and therefore power flows in these months due to colder temperatures. Temperature is therefore an important item of data for the real time rating of OHLs, in order to calculate the projected maximum current carrying capacity.

ENA ER P27 uses a probabilistic method for calculating ratings. (Ratings are either probabilistic or deterministic, where "deterministic" makes assumptions, e.g. for weather conditions, and "probabilistic" defines a set of weather conditions, e.g. the worst, and works out the current under those conditions).

Current CIGRÉ documentation is based on Engineering Recommendation P27, suggesting that international practice is similar to that in the UK [3].

2.3.2 Potential OHL DAR benefits and key factors limiting current in overhead lines

The potential benefits that may be expected when considering dynamic asset rating of OHLs within an electricity distribution network include:

1. Deferring network reinforcement by allowing more current to pass through the conductor when the weather conditions are favourable due to cooling;
2. Assisting with ratings when wind farms are connected (i.e. more power from the wind on a windy day – more cooling of the conductors).

However, the limiting factor in increasing the current flowing through the conductor is temperature and its effect on the Overhead line. The main effects include:

- **Sag** - In most cases, the thermal limit is defined by ground clearance that is sag of the conductor (not- thermal degradation of insulation or conductor melt temperatures as in cables or other equipment). In the UK, for distribution systems built prior to 1970, the Electricity Supply Regulations limited the rated temperature of OHLs to 50^oC. Some more recent lines have been limited to higher temperatures (up to 75^oC) due to the introduction of lighter conductors with higher strength/weight ratios. ENA ER P27 gives ratings at 50^oC, 65^oC and 75^oC. Literature is not clear if this is also a defining factor in covered conductors.
- **Conductor Grease** - To help with corrosion on aluminium lines and where appropriate its steel core, particularly in heavy industrial or coastal areas, grease is impregnated between the conductor strands during manufacture. L38/1 specifies that the greases are to be suitable for use up to 75^oC. As the grease used in aluminium conductor is not always stated and may not be known, above 80^oC the possibility of grease melt becomes a factor.

- **Conductor Annealing** - A further limit to the temperature at which existing aluminium OHLs can be operated is the loss of mechanical strength with time and temperature. When strung under tension, this leads to deformation over time with an adverse effect on the sag and therefore ground clearance. This effect shortens the lifetime of an aluminium overhead conductor when operated at high temperatures and shortens it considerably when operated above the annealing temperature of the conductor material. Aluminium Core Steel Reinforced (ACSR) conductors will begin to anneal between 90^{o}C and 100^{o}C (ACE 104 states an exact temperature of 93^{o}C). Aluminium anneals slower than copper but the difference is not significant.
- **Joints** - The weakest mechanical point in a constructed system is generally a joint. Various tests have been carried out on the effects of high temperature on compression splices commonly used on ACSR conductors at transmission voltages with effects on joints at over 100°C.

2.3.3 Overview of previous work on this technique

A number of past trial hardware and software solutions have been developed which work together to monitor a line's temperature, current, sag and tension [4-7]. Whilst these papers are aimed at Transmission line voltages, the principles may be applied to distribution voltages, despite a lack of practical measurements to verify the theory [8, 9].

Indirect methods of measurements using weather readings have also been used effectively at the transmission level in many countries [10].

Full Dynamic Thermal Ratings (DTR) with real-time monitoring have recently been developed and used in a number of countries [11, 12] yielding increases of 5-30% compared to the original static rating capacity [11, 13]. One such project funded by National Science Foundation in America, was the "Power Line Sensornet for enhanced Line Reliability and Utilization" [14]. The objective of this proposed Power Line Sensor Network (PLSN) was to provide continuous on-line monitoring of the power grid by using low cost autonomous, smart and communication-enabled Power Line Sensor (PLS) modules.

The connection of renewable generation to the transmission network has driven research into the dynamic rating of OHLs. One such paper looks into the benefits of the implementation of a DTR scheme in the Humber Estuary [15]. The research in question looked to develop a probabilistic model for seasonal off shore wind power as well as the development of seasonal dynamic thermal ratings of OHLs, taking into account past meteorological data. The paper explored the application of DTR of transmission lines to enhance the amount of wind power that can be connected to a transmission system close to its operating limit. It also suggested where the best location was for temperature monitoring facilities to enable DTR.

Research has been conducted into whether real-time line monitors are necessary, how many monitoring locations are required to rate an OHL and which monitoring method works best [16]. The analysis and accumulated field data findings indicate that dynamic thermal ratings for OHLs may be calculated based on either real time weather or real time tension data. For this multiple monitoring locations are required with the minimum number of monitors based on field measurements.

Other methods of evaluation of dynamic thermal ratings include the use of Multi-Layer Perceptron Network (MLPN) based parameter estimation schemes [17]. This method requires only temperatures and line current as inputs and has a simplified calculation providing a 'per span' granularity of the line.

A Dynamic Line Rating (DLR) scheme has been applied to a 132kV line in the UK by Central Networks (now part of WPD) for load management and protection to enable a larger penetration of wind generation in the English East Midlands [18, 19, 28, 29]. Another application of the DLR approach was installed by Northern Ireland Electricity (NIE) on the Omagh to Dungannon 110kV double-circuit line. The rating of the line is calculated dynamically from local weather measurements to co-ordinate allowed generation automatically. The English East Midlands trials resulted in 20% to 50% more wind generation being connected to the grid by taking into account the cooling effect of the wind.

The trials proved the DLR scheme to be a cost effective alternative to reinforcing the OHLs when constraints were present on the amount of generation that could be connected to the grid due to the fixed line ratings.

2.3.4 Overview of OHL dynamic asset rating

The practice of using OHL dynamic asset rating is to assess conductor temperature (the prevailing thermal state of the asset) and to estimate the additional load that the OHL could carry and still remain within a stated highest conductor temperature, for a given ambient air temperature.

In simple terms, for a given OHL, the temperature of the conductor (limiting factor for operation) is governed by the balance of the:

- heating effect of:
  - current flowing through the OHL; and
  - solar radiation (affected by the magnitude of local solar radiation and the absorptivity of the OHL conductor material);
- cooling due to:
  - convection (affected by wind speed, direction and air temperature);
  - radiation (affected by the emissivity of the conductor material and the difference between conductor temperature and air temperature; and
- Time constants associated with the above heating and cooling effects.

To establish a dynamic asset rating for an OHL, two elements are necessary:

1. A thermal model of the OHL is required to assess prevailing conductor temperature given previous load and ambient environmental conditions; and

2. A process is required that will iteratively increase modelled load current and calculate consequential conductor temperature (using the thermal model) until the limiting conductor temperature is reached. The load current that results in this limiting conductor temperature is the dynamic asset rating, or ampacity of the OHL.

The accuracy of the dynamic asset rating calculation is dependent on a number of key points:

- The models use mathematical constants within their calculated analysis such as DC resistance of conductor, conductor construction details and size, and solar absorptivity and radiation emissivity. In order to ensure the accuracy of the analysis these constant values need to be confirmed.
- Good operating data (e.g. air temperature, wind speed and direction) is key to estimating the conductor temperature. This has two aspects, one is the availability and accuracy of the data and the second is the time interval periods over which the data is measured.

In contrast to transformer DAR, the limiting asset temperature is reasonably measurable, and appropriate validation needs to occur between what the modelled conductor temperatures and the equivalent measured temperatures.

Minimum basic data requirements to allow an OHL thermal model to be constructed and validated, and for dynamic asset rating values to be estimated are:

- Ambient air temperature
- Wind speed and direction
- Solar radiation
- OHL current

2.4 Overview of approach to the technique trial

The high-level objectives of the technique trials (the deployment and trialling of techniques) can be generically summarised as:

- to understand the implementation of the technique;
- to understand operational capability of the technique;
- to inform changes to the modelling of the technique within the SIM;
- to trial an innovative communications network to support the techniques; and
- to capture knowledge and disseminate learning.

Learning Objectives originally associated with this technique are listed in Appendix B.

The overall process approach to the OHL DAR technique trial is shown in Figure 1

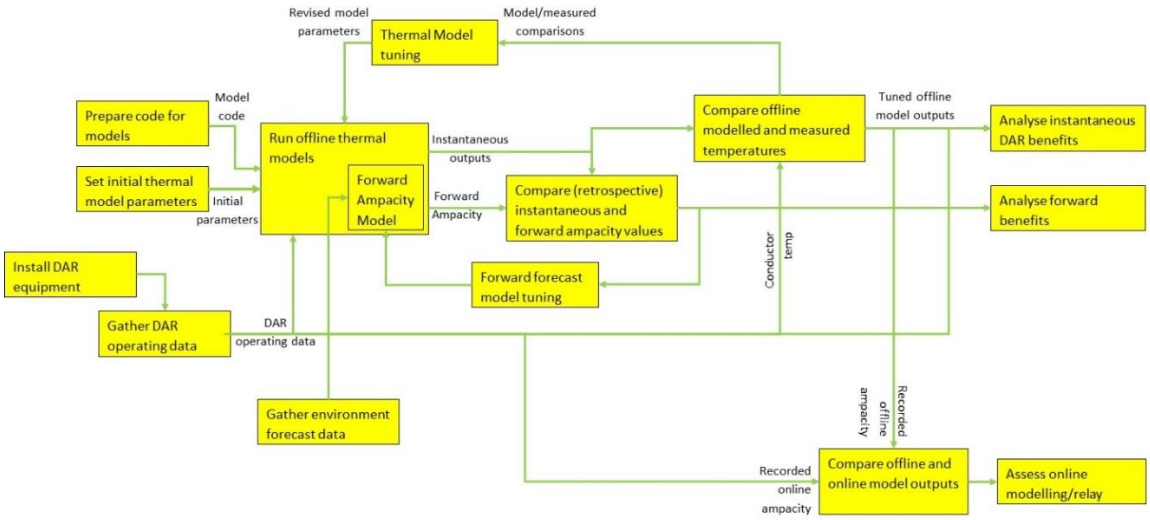


Figure 1: overall process approach to the technique trial

The technique trial therefore had a number of key elements:

1. Installation and commissioning of online DAR relay (including thermal model and parameters) plus associated input instrumentation;
2. Preparation of an offline thermal model (to allow tuning of thermal model parameters)
3. Tuning of thermal model parameters (applied to both the offline and relay thermal models)
4. Assessment of the benefits of instantaneous/of-the-moment DAR benefits
5. Assessment of the DAR relay/online or offline methods
6. Gathering of forecast environmental data;
7. Assessment of Forecast DAR benefits.

SECTION 3

Design, Construction and Commissioning

This technique trial sought to provide the data outlined in section 2.4. The technique trial was implemented on three 11kV OHLs coming out of Newport Pagnell substation to allow an offline thermal model to be created and validated, and for OHL dynamic asset rating values to be estimated. In addition, the online dynamic asset rating from the installed P341 relays were compared to offline models, and assessed.

3.1 Overview of selected sites

Three OHLs out of Newport Pagnell were trialled and are as follows:

- Way 9 to Aldrich Drive/Cotton Valley Tee, type Dingo 150mm^2 ACSR (type of conductor is obtained from the Network Design Manual) [20].
- Way 8 to Amway Tongwell, type ACSR Dingo 150mm^2.
- Way 4 to Riverside Park, 0.15 SCA: type ACSR Dingo 150mm$^{2.}$

3.2 As-installed equipment

3.2.1 Overview of as-installed equipment

Each of the trial OHLs was individually monitored for load current, and common measurements for solar radiation, wind speed, wind direction and air temperature were fed to the P341 relays. Figure 2 provides a schematic overview of the measurement and data collection arrangement.

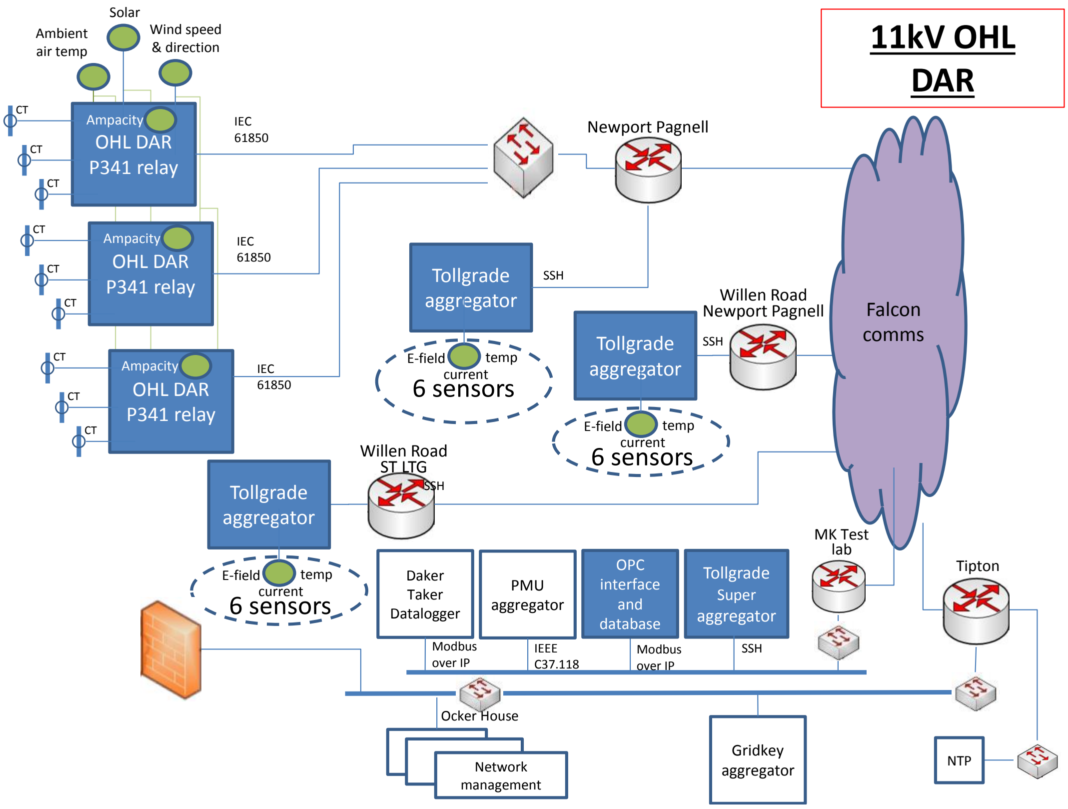


Figure 2: Schematic of installed 11kV OHL DAR scheme

In summary, the installed equipment comprises of:

- One Alstom P341 DAR relay (model P34131BB6M0710J, running software reference P341____6A_710_E) per monitored OHL, providing real-time calculations of conductor temperature and potential OHL ampacity, communicating via IEC 61850 over IP network;
- Use of existing CTs at 11kV feeder circuit breaker providing current measurement fed directly to the P341 relay;
- Gill Instruments Windsonic wind speed and direction sensor providing 4-20mA output signal fed to the P341 relay
- PT100 resistance thermometer, with light weight radiation shield, measuring ambient air temperature connected to Alstom iSTAT400 transmitter providing 4-20mA output signal fed to P341 relay;
- Kipp & Zonan SP Lite2 silicon pyranometer with PR Electronics 5115A signal calculator (mV to mA) to provide 4-20mA output signal fed to P341 relay;
- 18 Tollgrade LightHouse MV sensors independently providing measurements of current and OHL conductor temperature. The sensors are inductively powered devices that measure current, conductor temperature and electric field strength (proxy for voltage), and signal these values via IEEE 802.11 b/g Wi-Fi to a locally mounted Tollgrade Aggregator. The aggregator is a web-enabled device that manages onward transmission of measured values, analytical and status information from the OHL devices to the LightHouse Sensor Management System (SMS) software running on a Linux-based PC.
- 3 Tollgrade Aggregators providing communication interconnection between the Tollgrade sensors and the LightHouse Sensor Management System (software)
- 1 rugged Linux pc running LightHouse Sensor Management System software
- 1 pc running Matrikon OPC software suite

The P341 relay completes a calculation of conductor temperature for bare OHL based on either CIGRE 207 or IEEE 738 (user selectable), using: conductor material properties, ambient weather conditions, geographic orientation of the conductors, and conductor electrical current. Ampacity of the monitored line is calculated based on a user selectable maximum conductor temperature, and the measured ambient weather conditions.

3.2.2 OHL sensor locations

The primary purpose of the installed OHL sensors in the context of the scheme was to provide a dynamic measurement of conductor temperature that was required for thermal model validation purposes. Figure 3 shows the sensors. The sensors are inductively powered, and communicate via IEEE 802.11 b/g Wi-Fi to a locally mounted Tollgrade Aggregator. The aggregator is a web-enabled device that manages onward transmission of measured values, analytical and status information from the OHL devices to the LightHouse Sensor Management System (SMS) software running on a Linux-based PC.

Four of the eight 11kV feeders out of Newport Pagnell consisted of overhead sections adjacent or close in to the Primary substation. The three of these chosen on which to deploy the Lighthouse MV sensors were selected because of their differing azimuth. It was thought that by placing them in this way we would observe the effects of prevailing wind direction. On each feeder six sensors were deployed, one on each phase on the terminal pole at the start of each circuit and three placed along the feeder on alternate phases.

Figure 3 : Tollgrade Light House MV sensor

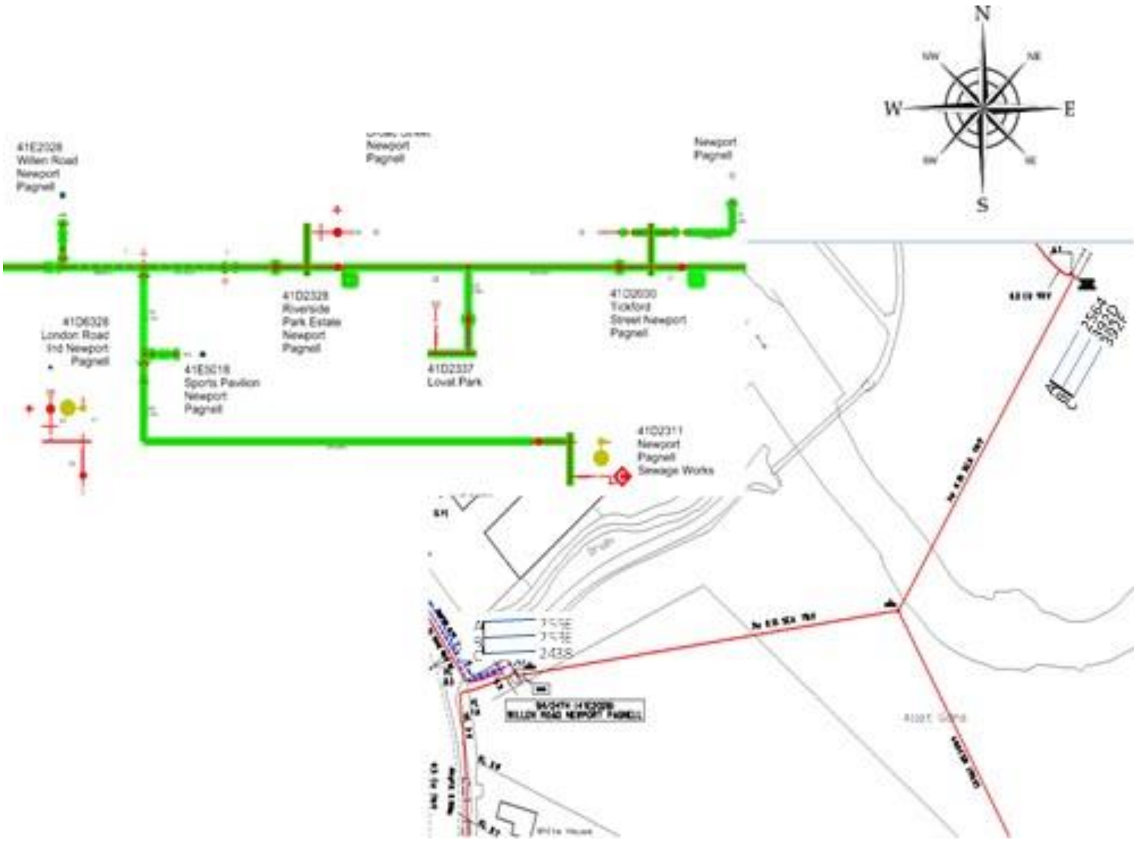


Figure 4 : Feeder 4 Tollgrade sensor locations

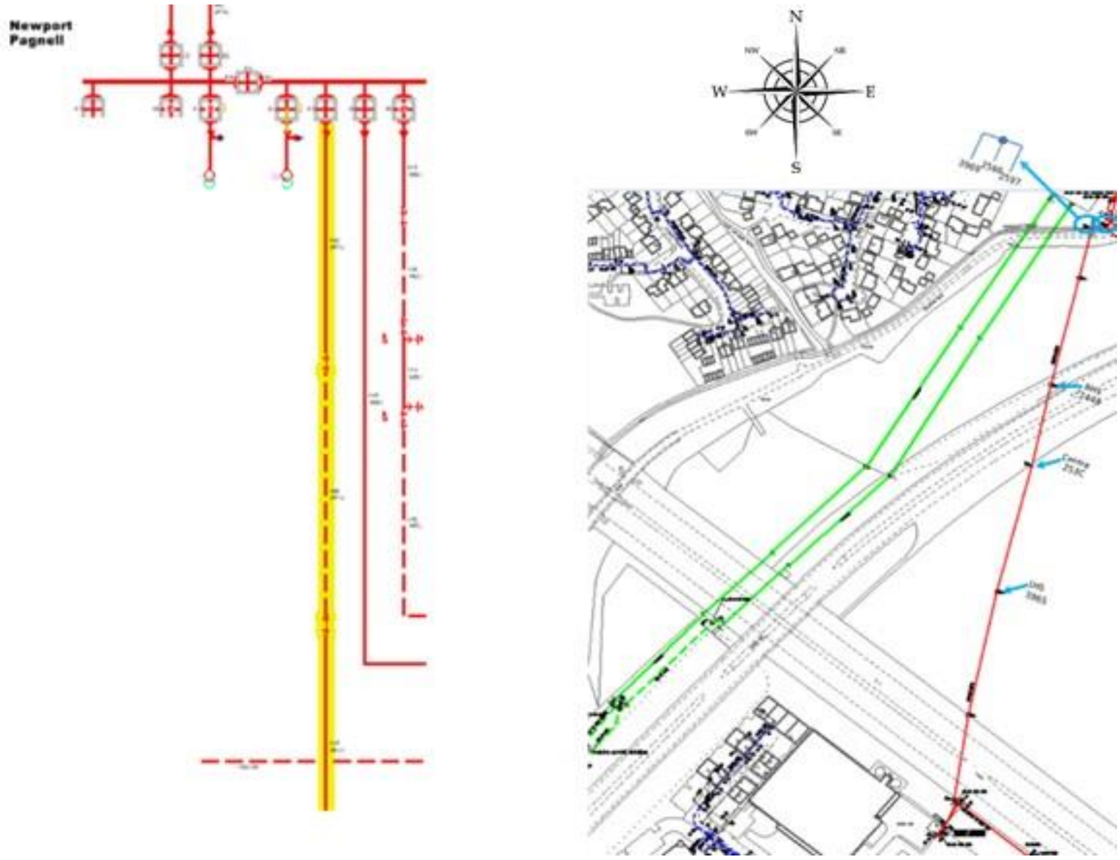


Figure 5 : Feeder 8 Tollgrade sensor locations

The Lighthouse sensors were applied to the conductors using live line techniques so there was no need for circuit outages. A Shotgun live line stick was used for this purpose (Figure 6). A particular point to note is that the sensor application screw is slightly larger than a standard live line tap screw and it was found that this could become jammed in a standard tapping rod head.

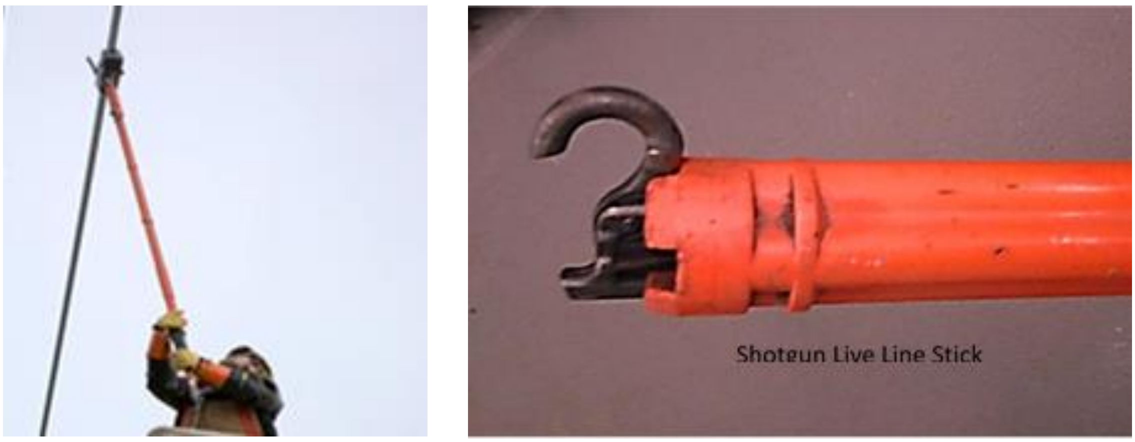


Figure 6 : Shotgun live line stick

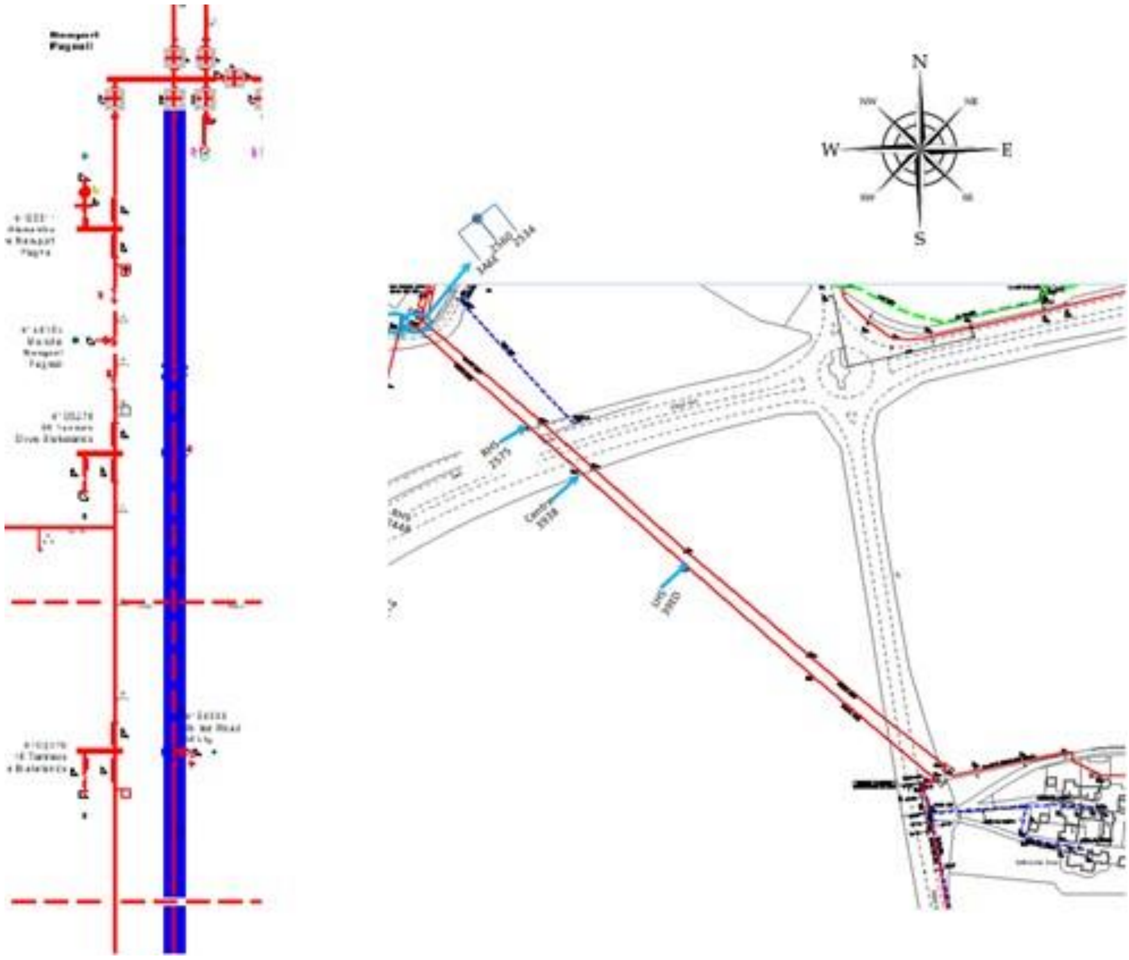


Figure 7 : Feeder 9 Tollgrade sensor locations

3.3 Data and data transfer

The high level trial measurement system flow of data can be summarised as follows:

1. Electrical current and weather data (wind speed, wind direction, solar radiation, and temperature) are measured and passed as analogue 4-20mA signals to the Alstom P341. These inputs are then collected as digital data from this relay and stored for offline analysis via a Matrikon 61850OPC server. The conductor temperatures are measured via Tollgrade Sensors, stored via Tollgrade aggregation hardware & software, and extracted for offline analysis;
2. The input data is used within the relay to calculate a dynamic asset rating value;
3. All data is collected for use in an offline mathematical model which uses a CIGRE thermal model coded into MATLAB to calculate the external line temperature for comparison with the Tollgrade measurement and replicates the behaviour of the relay to produce a value of ampacity.

4. The model calculated temperature and the model calculated ampacity were checked against the Tollgrade measured values and the relay determined value respectively and were deemed to be sufficiently accurate to indicate that the model is a good representation of the system for the input conditions experienced under the trial.

The data is recorded at 1 minute intervals for use in offline calculations.

3.4 Key learning from installation

3.4.1 Technique-Specific Learning

Learning from installation and commissioning is described below:

LP 1.	Data architecture and processing is critical to an innovation project. Significant post design phase development and refinement has been undertaken to establish functioning data capture and storage hardware, software and processes.

- Each measurement parameter should be clearly specified (e.g. sampled instantaneous, sampled average etc.)
- Failure to receive data values for all data requests should be anticipated in design, and an appropriate handling process established in advance
- Parameters that are processed/calculated from stored measurements should again be clearly specified, as should the process for proceeding when some/all underlying measurements are not available
- For the implemented trial system, some data anomalies did occur, due to data available and used by the relay not being transmitted to the data logger for use in the offline modelling. This led to limited periods of "null" data from the offline models, though these periods did not impact on overall findings.

LP 2.	Confidence in measured values is critical, complex, and may take time to achieve – particularly if the measured parameter cannot be obtained over an expected range to confirm calibration over a required range (e.g. wind speed). Careful consideration should be given to this issue in the planning phase, with the potential use of specialist service providers allowed for to assure appropriate validity and accuracy of measurement approaches.

- Examples of this issue are:
  - The external air temperature is measured using a thermocouple encased in a Stevenson shield. On hot days this temperature appears to be higher than expected indicating that the shield may not be operating as anticipated.
  - The Tollgrade temperature device is located in a housing which in itself may be impacting conductor temperature measurements most specifically at cooling by

providing a thermal mass. Improvements relating to quality of measured conductor temperature are recommended.

LP 3.	Careful consideration should be given to the use of specialist service providers to install/calibrate specific instrumentation.

Issues with measured data suggest that:

- Validation processes were considerably more detailed and complex than implied by the initial use-case documentation and issues that needed consideration included:
  - Poorly described manuals with information on relay settings and safety margins
  - Data refinement and filtering
  - Determining values for fixed constants such as thermal absorptivity;
  - It is difficult to establish data which covers every aspect of the model input range as this is heavily dependent on the weather. Data tends to be clustered round normal conditions with much less data available at extreme conditions. Ideally the trial would want ambient condition ranges that show:

- ambient temperature range of -10^{o}C to 30^{o}C
- perpendicular wind speed 0-15m/s
- solar 1-1000W/m^2
- Ideally want current/circuit loading (for purposes of calibration conductor temperature calculation models)
- Loading from 0-at least 50% of static rating

However collecting data over this range was not possible.

The data collected as part of the trial had a significant quantity of erroneous data. Table 1 shows the breakdown over each 8 hour period of where the data was good within this period and where there were bad areas (typically the data is fixed through the post processing when it is not clear what this should be and the rating is then also fixed and defined as uncertain).

Data OK	60%
Data Faulty	40%

Table 1 : 8 hour data quality

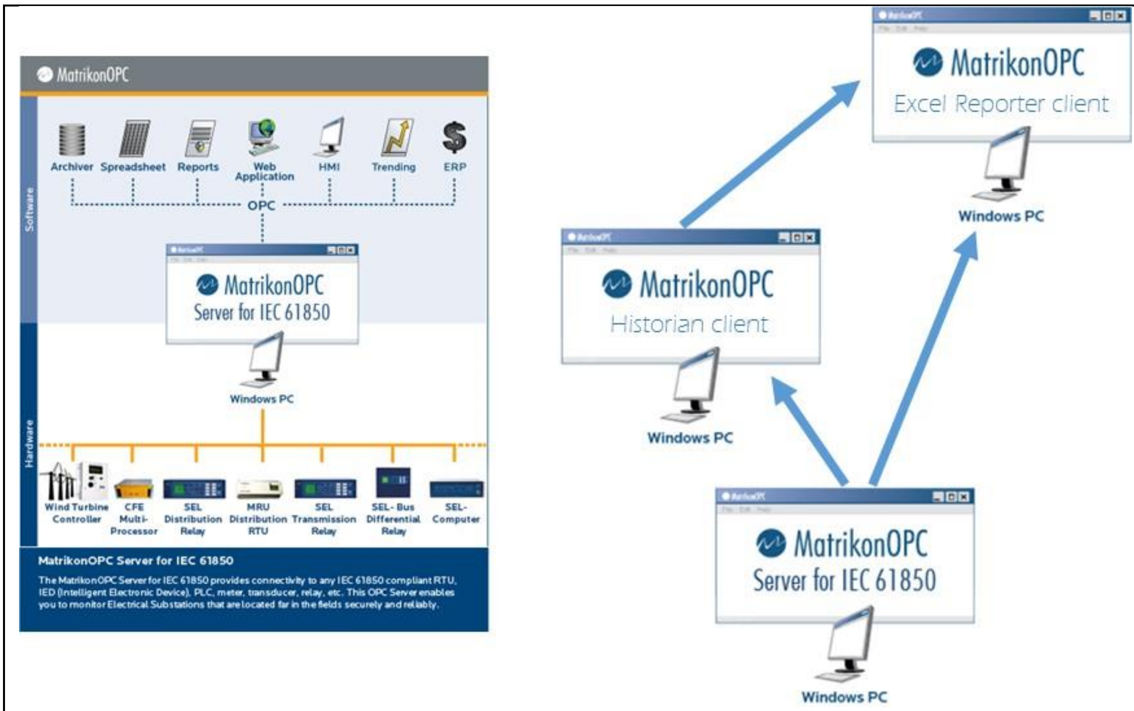
3.4.2 Generalised and Cross-Technique Learning

LP 4.	Implementation gave a further opportunity for review of design, and as installation/commissioning progressed some aspects of design intent/detail were changed:

- Initial design was for each of the three circuits being monitored to have individual environmental monitoring.
- As all three circuits originated from the same primary substation this design intent meant there would have been three of each type of instrument installed adjacent to each other.
- Initial construction installed one set of measurement instruments.
- Commissioning then amended design intent to have one set of instruments that feed the same values to all relays.

LP 5.	Simple data capture and storage infrastructure, that is understood and within the control of the project team is imperative:

- Delays were experienced in implementation of the original storage solution which was an extension of the control room system, Power On Fusion (PoF). It became apparent that the centralised storage would not be sufficiently flexible for the early stages of an innovation project where initially established requirements are confirmed or modified.
- Installation of interim data acquisition and storage system were undertaken



OPC - **O**LE (Object Linking and Embedding) for **P**rocess **C**ontrol - is a software interface standard that allows Windows programs to communicate with industrial hardware devices

Figure 8: Outline of OPC

- Two systems were trialled, and an OPC software suite from Matrikon was selected. This addressed the core requirement to collect data from the IEC 61850-configured P341 relays, but also allowed scaling options to include Modbus enabled devices (also included in the project).

LP 6.	Significantly more work was involved in the commissioning of the system than was anticipated:

Each instrument required individual configuration, potentially involving establishing serial communications with the device. This was unexpected and required the use of Hyperterminal which is no longer distributed in Windows 7.

Signal conditioning equipment within the DAR cabinet (translating instrument output for input the P341 relay) also required configuration, though this was only discovered when nonsensical signal values to the P341 relay were reviewed. This prompted wider realisation that Factory Acceptance Tests (FAT) had not tested the whole supplied system (instrument output to P341 relay output)

Tuning of P341 relay configurations – whilst the relays were supplied with a level of configuration, final setting of configurations (including IP addresses, timer servers etc.)

was required. This necessitated acquisition and installation of manufacturer bespoke configuration software, and a learning cycle associated with usage.

LP 7.	Initial overall system testing revealed key importance of good manufacturer support and documentation:

Given the extensive work required to commission the system as a whole, basic tests to prove expected operation of the P341 relays were undertaken. This revealed key insensitivity to wind speed.

Review of the Factory Acceptance Test (FAT) documentation also revealed this insensitivity at the time of testing but was not picked up on by any of the parties involved.

The data insensitivity was eventually tracked by the manufacturer to a menu setting which was poorly explained within the operational manual provided

SECTION 4

Thermal Models

4.1 Overview of thermal models

To estimate the benefits of this technique the following approach has been taken.

1. A model of the OHL was coded to calculate conductor temperature compared to measured trial data over the period of a year for a range of real world input weather and load values to validate the model.
2. The model was used to generate an ampacity value based on the measured input data and compared to that generated by the relay.

Figure 9 shows the high level data flow and approach to the method of validation in steps 1 and 2. The flow of data can be summarised as follows:

- Electrical current and weather data (wind speed, wind direction, solar radiation, and temperature) are measured and passed as analogue 4-20mA signals to the Alstom P341. These inputs are then collected as digital data from this relay and stored for offline analysis via a Matrikon IEC61850 OPC server. The conductor temperatures are measured via Tollgrade Sensors, stored via Tollgrade aggregation hardware & software, and extracted for offline analysis;
- The input data is used within the relay to calculate a dynamic asset rating value;
- The data is collected for use in an offline mathematical model which replicates the behaviour of the relay.
- Mathematical models relating to the thermal dynamics of the OHL recommended by CIGRE was coded into MATLAB (referred to as the Offline models) and are used to calculate an ampacity and external conductor temperature (dynamic and static) value for comparison to the Alstom relay's ampacity value, and the measured conductor temperature respectively;

1. The model generated ampacity value was modified to create an 8hr fixed value of Ampacity rather than a continuously changing value.
2. The model generated 8 hour ampacity was compared to the static rating to look for benefits to Network operating conditions that could be realisable.
3. Day ahead and week ahead weather predictions were modified to meet the input requirements of the model and used to generate a predicted 8 hour ampacity.
4. The predicted ampacity was compared to the model generated 8 hour ampacity using the measured weather data.
5. A statistical tool to determine what safety margin offset should be applied to predicted values was developed.

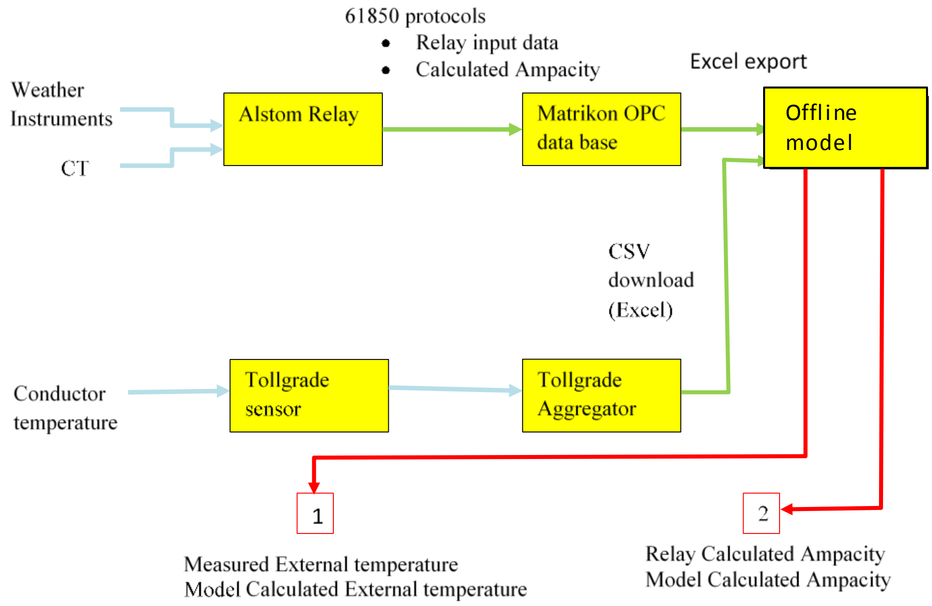


Figure 9: Data flow and measurement/calculation comparison for OHL DAR

There are three well-known standards bodies proposing models to be used for determining the rating of bare OHL conductors:-

- IEC/TR 61597
- IEEE 738 - 1993
- CIGRÉ WG 22.12 (published in Electra 144 – 1992).

A comparison of the output of each of the models, for the same input conditions, for an ACSR conductor (LYNX 175mm2) has been reported by a team at Durham University [21]. The IEC and IEEE model matched closely over wind speeds greater than 0.5m/s. The Cigré and IEEE models matched closely for wind speeds below 3.5 m/s. All 3 model outputs correlate between 0.5m/s and 3.5m/s.

A number of previous studies have been undertaken in the past on ratings of OHLs, most notably by EA Technology[22] who looked at three different conductor types at a couple of purpose built sites in different weather conditions. Their data, gave a reasonable level of comparison to the Cigré modelling method. The Cigré model "Thermal behaviour of overhead conductors" [23] has been selected here as the predictive model because it allows comparison between results from an EA Technology study on a similar subject [22] and the model internal to the Alstom P341 relay. The Cigré equations give the same results to the equations used to determine the P27 ratings at the P27 design conditions with a wind angle delta of 45^{o}.

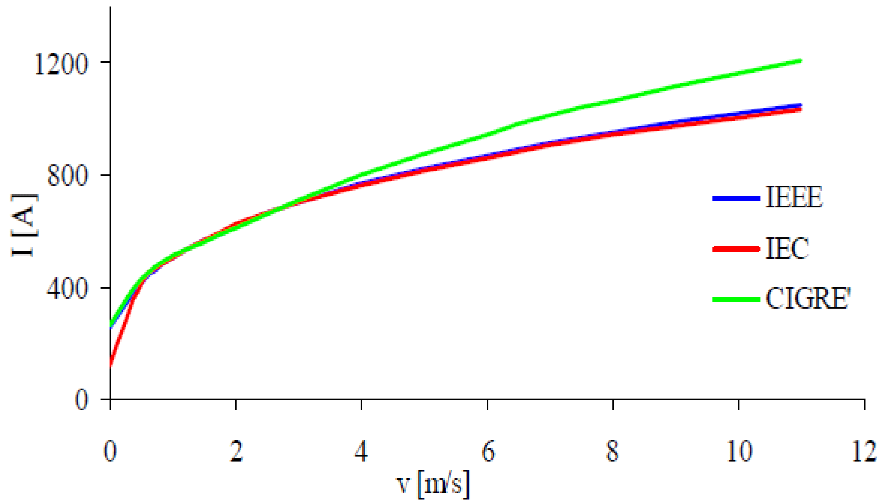


Figure 10 : A comparison of the modelling results undertaken by Durham to compare different models for a Lynx conductor for varying wind speed.[21f]

The Cigré model looks at the thermal conditions in a system as shown in Equation 1.

The thermal Equilibrium in steady state is given by:

Heat Gain = Heat Loss

$$P_j + P_m + P_s = P_c + P_r + P_w \quad \textbf{Equation 1}$$

Where

P_j = Joule heating

P_m= Magnetic heating

P_s = Solar heating

P_c = Convective cooling

P_r = Radiative cooling

P_w = Evaporative cooling

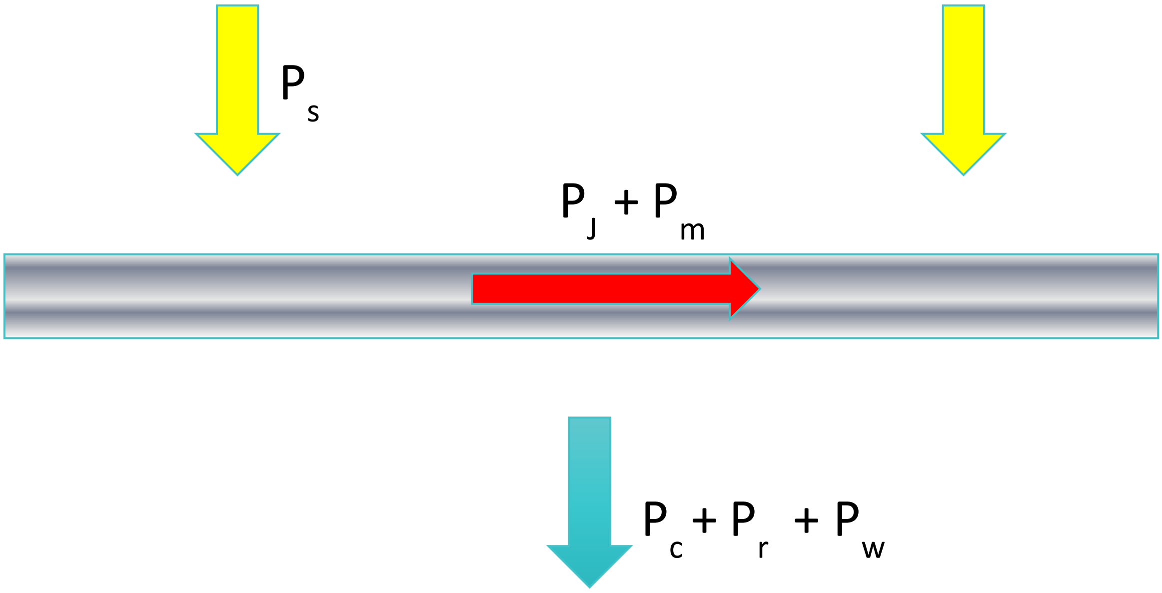


Figure 11 : High level heating and cooling effects

The model has a number of assumptions listed below;

Heating assumptions:

- Method is approximate and valid only up to current densities of 1.5A/mm^2.
- Joule heating includes a temperature correction co-efficient and an approximation for resistance change due to skin effect.
- A multiplication factor on the current is used where appropriate to include the effect of the steel core.
- Solar heating is simplified to $P_s = \alpha_s SD$ where α_s is the absorptivity of the conductor surface.
- Corona heating is only significant with high surface gradients and assumed negligible in this case.

Cooling assumptions:

- Forced convective cooling is largely based on empirical factors (using the Nusselt number, the Reynolds number, the Grashof number and the Prandtl number). The cooling also varies with the sine of the angle of the wind to the conductor.
- The cooling deals with a number of cases including natural convective cooling, low wind speed (<0.5m/s), forced convective cooling, radiative cooling.
- Evaporative cooling is considered negligible as the effect of water vapour in the air or water droplets flowing around the conductor do not change the evaporative cooling. This is more significant when the conductor is wet.

The thermal equilibrium in unsteady state is shown in Equation 2.

Heating effect = Heat Gain - Heat Loss

$$mc\frac{dT_{av}}{dt} = P_j + P_m + P_s - P_c - P_r - P_w \qquad \text{Equation 2}$$

Where

m = mass per unit length

c = specific heat capacity (varies with temperature)

T_{av} = average of the core and surface temperature

The heating characteristic in unsteady state can be approximated to that in Figure 12

- For a step change in power the differential equation can be solved and represented by an exponential curve with a time constant.
- The time constant, τ, is dependent on the conditions at the time and is typically between 5 and 20 minutes.
- A similar curve for cooling exists.

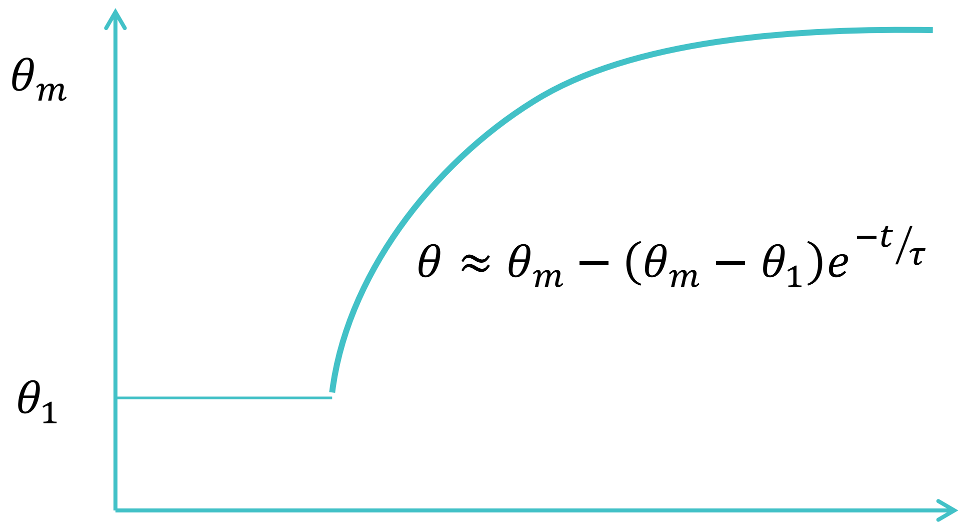


Figure 12 : Step change in current with time showing dynamic heating effect

The majority of the data used in the modelling was provided by Western Power Distribution. Additional OH line specific data has been obtained as follows:

- Mass of the conductor [24]
- Heat capacity and heat capacity co-efficient from the CIGRE working group "zebra" conductor example [23]
- Some of the data relating to the Dingo conductor has been taken from calculated values using OHRAT the EA Technology program relating to the static calculation of

ratings of OHLs including; Diameter, DC Resistance, resistivity and the temperature co-efficient alpha.

These parameters have been entered into the offline Matlab model along with the data for line loading to investigate OH line dynamic asset rating.

4.2 Model vs measured conductor temperature across seasons

There are two sides to the thermal modelling of OHL's; to calculate and compare the external conductor temperature reported by the Tollgrade device and to understand the dynamic asset rating as reported by the relay.

The validation process works by comparing the measured temperature of the line with the calculated line temperature. To show this working across the seasons a set of sample days similar to those used in other techniques have been chosen. The results of comparing the measured to the modelled external conductor temperature are shown in Appendix I using reported weather data from Appendix D for the sample days in Table 2.

Season	Date	Day
Winter	7th Jan 2015	Wed
Winter	11th Jan 2015	Sun
Spring	28th May 2014	Wed
Spring	22nd Mar 2015[2]	Sun
Summer	25th Jun 2014	Wed
Summer	29th Jun 2014	Sun
High Summer	23rd Jul 2014	Wed
High Summer	20th Jul 2014	Sun
Autumn	24th Sept 2014	Wed
Autumn	9th Nov 2014	Sun

Table 2: Seasonal analysis

The external temperature measurement that has been used to validate the model is prone to measurement reporting failure, however the sensor values largely correlate. The measurement only shows a change to the nearest 1^{o}C (hence the stepped waveform in some of the graphs in Appendix I).

[2] On Feeder 4 because of lack of temperature measurement on feeder 8 in Spring

The range of input data available from the trial is shown in the heat map in Figure 13.

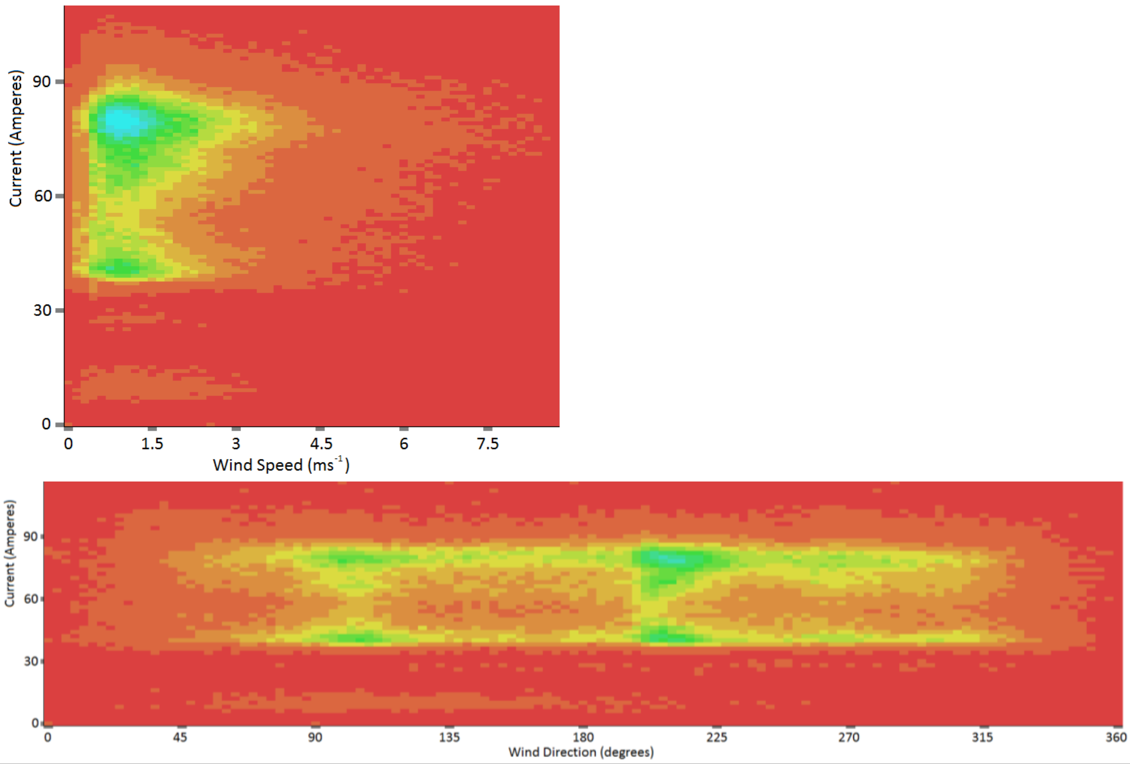


Figure 13: Heat Map-style diagram showing variation in wind speed and wind direction as measured at Newport Pagnell Primary Substation

Clearly a wide range of ambient and operating conditions are required to assess thermal models. Figure 13 is an example of how this range of ambient/operating circumstances was logged, and illustrates the variation in wind speed and wind direction as measured at Newport Pagnell Primary Substation. This clearly shows wind speeds are most frequently measured as being in the range 0.5 – 3 m/s, with directions predominately from the south west, and also the east. Similar variation can also be seen in solar radiation and ambient air temperatures.

LP 8.	It is difficult to establish data that covers every aspect of the model input range- as this is heavily dependent on the weather. Data tends to be clustered round normal conditions which provide valuable learning for the majority of occasions. However, very valuable learning also occurs at extreme conditions, for which much less data is available. Ideally the trial would want to see ambient condition ranges that show: – ambient temperature range of -10°C to 30°C – perpendicular wind speed 0-15m/s – solar 1-1000W/m^2 Ideally conditions with different current/circuit loading (for purposes of

	calibration conductor temperature calculation models) 0% to at least 50% of static rating should be obtained.

LP 9.	Close correlation of modelled to measured conductor temperature has been achieved under most circumstances; however, on very hottest of days the measured line temperature appears to cool much slower than the modelled temperature. 90% of all modelled external conductor data is within 6^{o}C of measured.

In terms of the comparison of the model with conductor temperature, close correlation has been obtained under most scenarios, with a good match to absolute min/max values. Where the line temperature is less than 20^{o}C absolute, the heating and cooling match reasonably well. However, on hotter days (see high summer curves in Appendix I), the line appeared to cool much slower than the model. It is suspected that this is related to the Tollgrade device and its thermal mass.

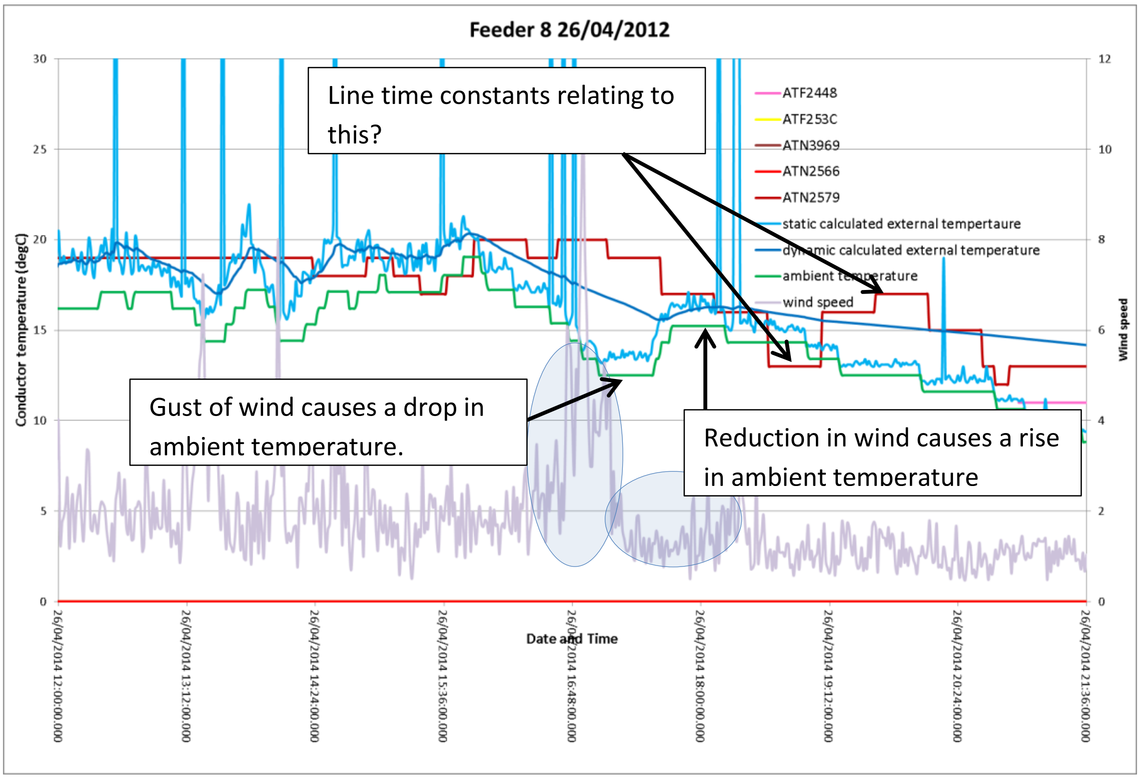


Figure 14 : Line temperature with changes in wind speed

The thermal time constants for heating and cooling to calculate the dynamic as opposed to the static temperature are different depending on whether the line is heating or cooling. It would appear that the heating time constant matches up reasonably well.

However, the line cooling is reported slower than the model on hot days. The cooling thermal time constant is dependent on:

- The mass of the line (0.506kg/m)
- The thermal capacity of the line (897J/kg/K as recommended in the standard)
- The difference in previous and current line temperature to ambient temperature and the power being used to heat the cable.

From Figure 14 the time difference between the ambient temperature reduction and the line reduction is 1 hr and 35 minutes and the secondary peak is 2hrs and 5 minutes behind the ambient temperature. This is significantly different from the time constants indicated in standard 207 ("thermal requirements of overhead lines"). The reason for this difference is not completely understood – but a possible hypothesis is that the Tollgrade device limits the cooling to the line at that point by providing a protective barrier to the wind. The thermocouple is encased in a case clamped onto the overhead line as shown in Figure 3.

If the thermocouple is encased then it is possible that it gets directly affected when the line is heating up due to current flow (hence the thermal constant is accurate for heating), however is not directly subject to the effect of the cooling and therefore the thermal constant for cooling is not appropriate as suggested below.

Figure 15 : Line temperature measurement device effect on cooling

If we consider that the ambient air temperature has already cooled to 5°C from 15°C due to the cooling effect of the wind, (where r_1=8.3mm and r_2 is estimated at 50mm), the thermal time constant is approximately equal to:

$$\boldsymbol{\tau = \frac{\rho c_p V}{h A_s}} \qquad \textbf{Equation 3}$$

Where ρV is the mass, c_p is the heat capacity (=0.897 for Al), h is the heat transfer co-efficient (approx. 1 for a free gas) and A_s is the surface area. From a very simplistic perspective, if 1m of aluminium cylinder at r_1 = 8.3mm was replaced with aluminium cylinder at r_2=50mm then the thermal time constant would increase by

$$\tau_{increase} = \left(\frac{r_2}{r_1}\right) = 6\ times$$

So a 10 minute time constant could become an hour for the same step change when the conductor in encased.

The model external temperature for a week day and weekend show no noticeable difference in accuracy. In fact, the loading in High Summer is the only time when a noticeable difference in week day/ week end loading having an effect on the line is visible. Therefore the loading on the line is being modelled correctly within these loading parameters. The ambient temperature has ranged from <0 to >30^{o}C with only minimal differences in measured temperature – all of which occur on hot days.

4.3 Model vs relay reported ampacity across seasons

It was not immediately clear that the relay-reported ampacity and the offline-model ampacity were comparable even though they used the same CIGRE model as a base to calculate external conductor temperature.

Figure 16 shows the model calculated DAR rating using relay reported unmodified weather data compared to the Ampacity calculated and reported by the relay. The graph shows a greater variation in the offline calculation of the DAR as this is highly dependent on the instantaneous wind speed measurement. Data smoothing and data propagation delay associated with this calculation along with a safety margin needed to be included into the offline model to allow the offline modelled results to more accurately represent the relay reported results. Implementing this in the model shows an improvement in the comparison, with most values being within a couple of amps.

Attempts to match the model to the relay have led to the following changes in the model;

1. Average the wind speed by a rolling average of 10 data points.
2. Simulate a time delay to the DAR to compensate for the averaging and calculation delay of around 10 time steps
3. Add a safety margin of 10% (6^{o}C) into the calculation of DAR
4. An error margin of around 0.5A on calculating the DAR should be set

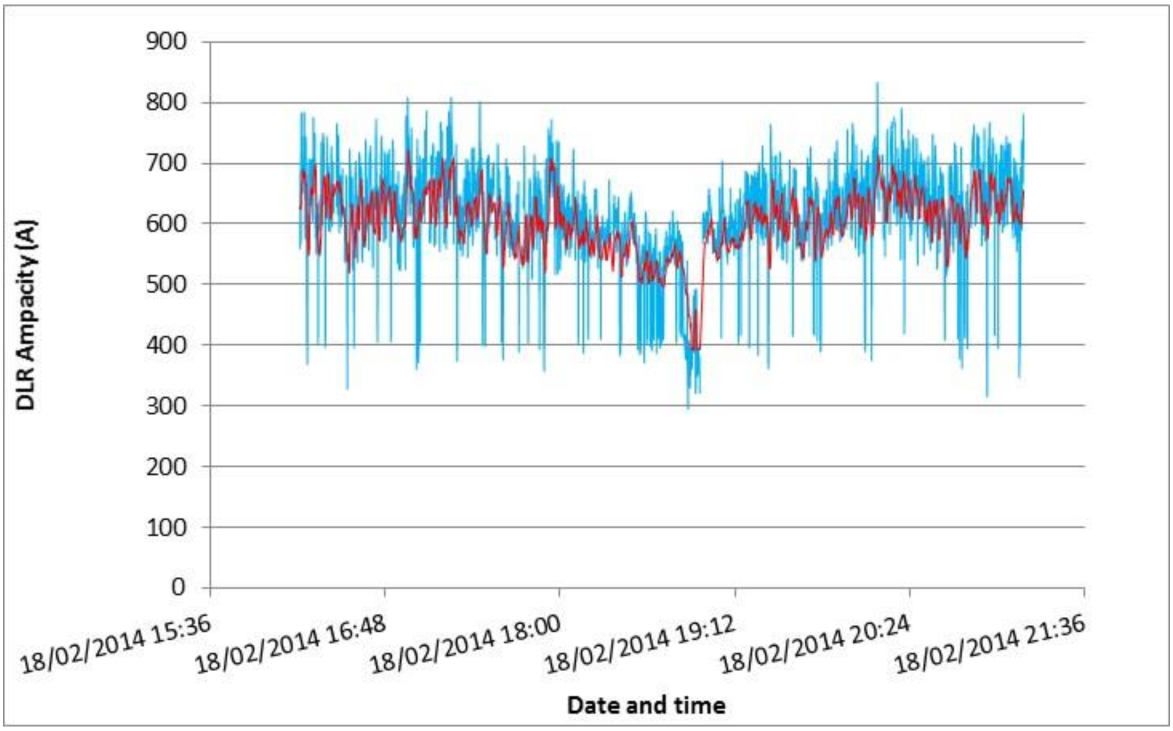


Figure 16 :DLR Ampacity against time (relay reported ampacity (red) and unmodified model values (blue))

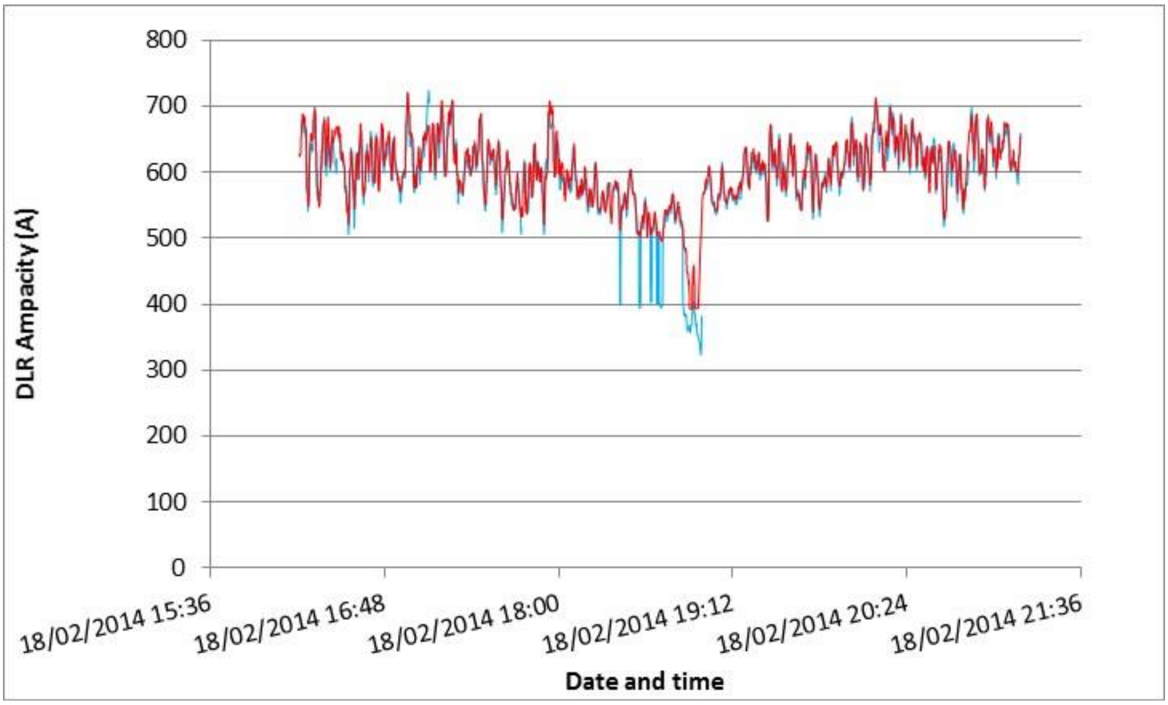


Figure 17 : DLR Ampacity against time (relay reported ampacity (red) and adjusted model values (blue))

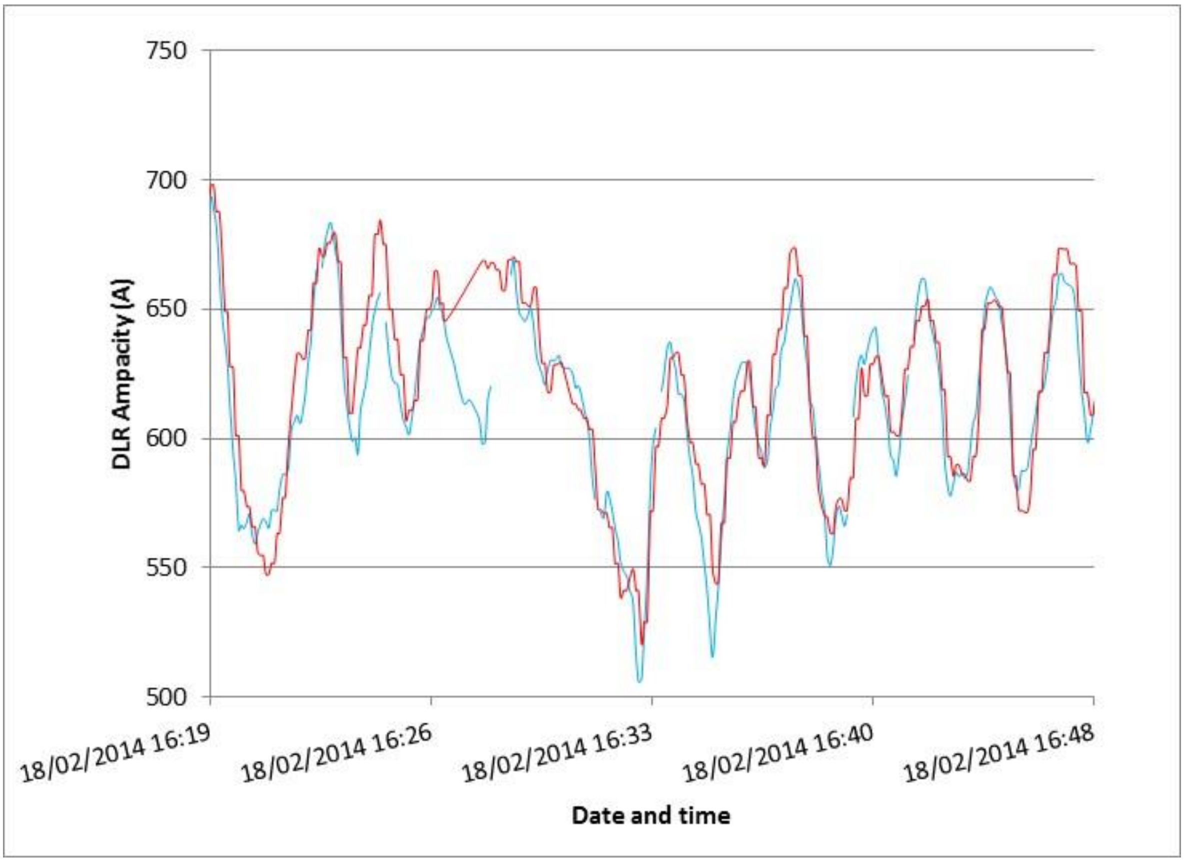


Figure 18 : Close-up of DLR Ampacity against time (relay reported ampacity (red) and adjusted model values (blue))

Other minor issues that resulted in differences between model and relay are as follows:

- At high wind speed and high wind angle an update to the published standard is required. Work by CIGRE has resulted in the questioning of the constants and they recommend use of adapted constants (Table 3 and Table 4), based on investigations by Isozaki et al. [25]:

The following equation remains as per the working group standard:

$$Nu_{90º} = B\,Re^{n}$$ **Equation 4**

Where the coefficients B and n depend on the roughness R_s of the surface of the conductor, $R_s = d/[2(D - d)]$, where d is the diameter of the wires in the outermost layer, and D the overall diameter.

Roughness, R_S	B	n
$R_s < 0.1$	1.566	0.340
$R_s > 0.1$	1.325	0.362

Table 3 : Coefficients proposed by Isozaki et al. [25] for calculating forced convective heat transfer from conductors with steady crossflow of air.

The following equation based on wind direction is adapted from the original by Isozaki et al. [25]:

$$\frac{Nu_{\delta}}{Nu_{90^{\circ}}} = \left[C \cdot \mathrm{Re}^{m_3} \cdot (1 - \sin\delta) + \sin\delta\right]$$

Equation 5

Where the coefficients C and m_3 depend on the roughness:

Roughness, R_S	C	m_3
$R_S < 0.1$	6.124	-0.314
$R_S > 0.1$	5.604	-0.327

Table 4 : Coefficients proposed by Isozaki et al. [25] for adjusting angle of incidence in forced convective heat transfer.

- At very high wind speeds the relay calculates dynamic asset rating higher than the offline model, this is visible in the data for Wed 7th January in Appendix I. The ampacity is clearly a function of the coefficients, which have higher impacts under these conditions. There was no access to the relay information on the constants used.
- To match the thermal heating the solar absorptivity data in the model has been set so that the model calculated external temperature matches the thermocouple value. This is higher than that in the relay. Therefore the reported relay DAR values within Appendix I are a fraction higher on hot days since the heating is not taken into consideration in the same way.

The model calculated and relay reported data for the 10 sample days in Table 2 are shown in Appendix I. What is clear from the representative data is that the relay receives the data locally, but it doesn't always transmit the wind direction or wind speed value, and while the relay continues to calculate a dynamic rating based on measured data, the offline model is dependent on data which has in essence frozen. Periods where model ampacity and relay ampacity look different occur at these points.

The thermal modelling is a means to calculating an OHL ampacity value (i.e. the maximum current that can pass through a line without the temperature exceeding ratings). However, the value reported by the relay and replicated by the model is very dependent on both wind speed and wind direction which change significantly in "real time".

The following lessons have been learnt in the process;

LP 10.	Equipment has information that is required for validation but not easily available. For example, – The relay appears to average wind speed over 10 data points and then has a 10 time step delay in reporting the answer – The relay appears to have an inbuilt error margin of around 10% or 6°C when the ampacity is calculated. It is not clear what the accuracy of the relay is; however, based on modelling calculations it is definitely greater than 0.5A.

LP 11.	Solar radiation effects are sensitive to the constants chosen for thermal emissivity and solar absorption. The default values of the relay were low compared to published literature and have been raised in the model to get better correlation of conductor temperature in hotter weather.

LP 12.	Some of the constants used within the model are not available for adjustment. An example would be one of the constants relating to roughness of the conductor which heavily influences cooling. Indications are that this value is appropriately set.

LP 13.	The ampacity as reported by the relay is not particularly useful as the value fluctuates significantly in response to a continually changing wind speed and wind direction. A mechanism for averaging this is required to provide a useful measure. See Section 6.

LP 14.	There are some periods where there are ampacity gains and some, where ampacity is calculated lower than static rating. These periods do not generally coincide with temperature (day/night) but are more heavily dependent on wind speed and effective cooling. On the whole, the average calculated ampacity (considered over an 8 hour period) is above the static rating in all months except September.

LP 15.	September 2014 was unseasonably warm and dynamic calculated ampacity was closer to the summer rating than the autumn rating. We recommend that this data is reported and examined in line with P27 and if agreed a summer rating rather than autumn rating may need to be applied in September.

LP 16.	In order to utilise dynamic asset rating it would appear more beneficial to know in advance what the rating of the line will be rather than its real time value as reported by the relay (as this is ever changing). Therefore an offline model using predicted weather is potentially more valuable than an on-line relay.

LP 17.	The 10 minute time constant of the line means that its variability and speed of change make it inappropriate as a technique for planning in the SIM confirming initial assumptions

Additional points relating to the learning are as follows:

LP 18.	The thermal model is representative of the asset performance under conditions tested to date.

LP 19.	Ambient temperature, wind direction, wind speed and solar radiation all have an impact on dynamic asset rating. Due to the non-linear nature of this an offline computer program will allow dynamic rating to be calculated based on weather conditions.

SECTION 5

Dynamic Asset Rating

5.1 Practical ampacity across seasons

The relay gives a dynamic ampacity that is highly variable due to the fluctuations in wind speed and wind direction and this is of limited value to an operator. A far better approach is to define a fixed rating based on an 8 hour period in which the temperature of the conductor never exceeds its limits. This produces a line in three sections similar to that below in Figure 19 where the rating trims the bottom of the dynamic rating. It is this value of 8 hour rating which is used within the benefits section.

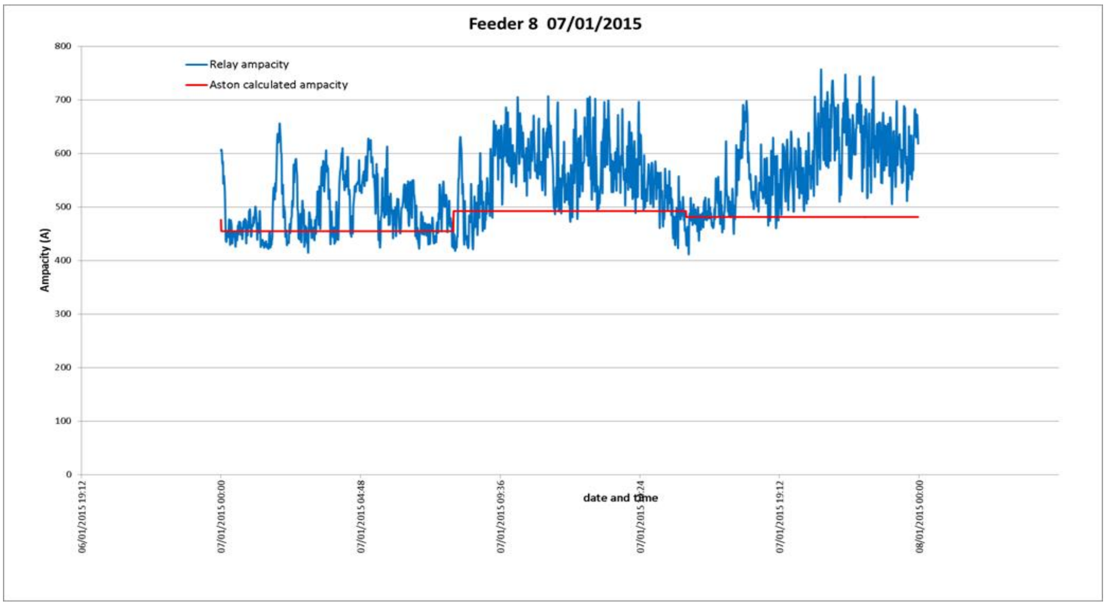


Figure 19 : Calculated Ampacity Winter Wednesday 07/01/15

LP 20.	A dedicated DAR relay is not essential, other computing devices/systems could perform real-time assessment calculations (e.g. the network management system), if these are required. The OHL/cable/transformer-variant relays provided limited functionality and both variants were inflexible. In addition, offline modelling (an alternative to real time relays) was particularly important because it allowed extension of the work into forecasting of future ampacity – see points below about forecasting ampacity.

The 8 hour rating is calculated in a similar manner to the "of the moment" ampacity. The current is applied as a fixed value over 8 hours and increased with the reported environmental conditions until the temperature at any instance exceeds the limits. The results are presented in Section 7.

SECTION 6

Forward Ampacity based on forecast ambient conditions

6.1 Overview of forward ampacity

"Of the moment" ampacity may not be useful from an operations perspective as to take advantage of ampacity it is necessary to know what this is going to be. The forward ampacity is dependent on

- accuracy of forecast ambient conditions, and
- the introduction of probabilistic approach that seeks to manage key risk of exceeding thermal limits

LP 21.	If predicted ampacity is going to be used then dedicated real time weather measurement in conjunction with a relay is not required in all instances. The process can be undertaken from a desktop computer. It is highly likely that some limited weather monitor would be required to maintain cross-checks between forecast ampacity and instantaneous ampacity for assurance purposes.

6.1.1 Description of derivation of forward ampacity values

The approach takes ambient parameters from weather forecasts and provides shapes to these values over time. From the arrays of shaped ambient conditions, a profile of maximum current values is iteratively calculated that causes the asset to heat up to its limiting temperature. This maximum electrical current profile allows the ampacity of the asset to be assessed based on the forecast time-varying ambient conditions. This method of estimating future ampacity was tested by comparing the forecast ampacities against outturn of-the-moment ampacities. To take into account the forecast error a safety margin factor was established to allow for this uncertainty and allow ampacity to be predicted for a fixed confidence level. Comparison of the day ahead and week ahead predicted weather over the seasons is shown in Appendix E and H respectively.

LP 22.	It is difficult to predict weather especially wind speed and wind direction with any accuracy. An error margin needs to be included in the calculation of ampacity to deal with this uncertainty.

6.1.2 Predicted Weather Data

The predicted weather data was downloaded using html code (see Appendix J) from the BBC weather website every morning for the local area, with the day-ahead and week-ahead (7 days) forecast stored for comparison with the measured data. This data was downloaded and stored in an excel spreadsheet (see Appendix L for an example).

The day ahead weather is represented as shown in Figure 20:

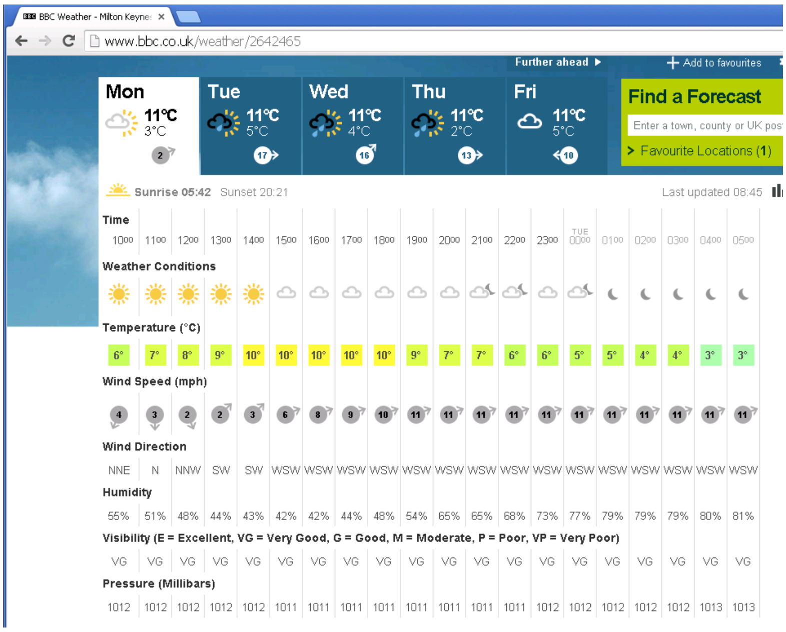


Figure 20 : BBC day ahead weather prediction

While the week ahead data has even less predicted data reported as follows:

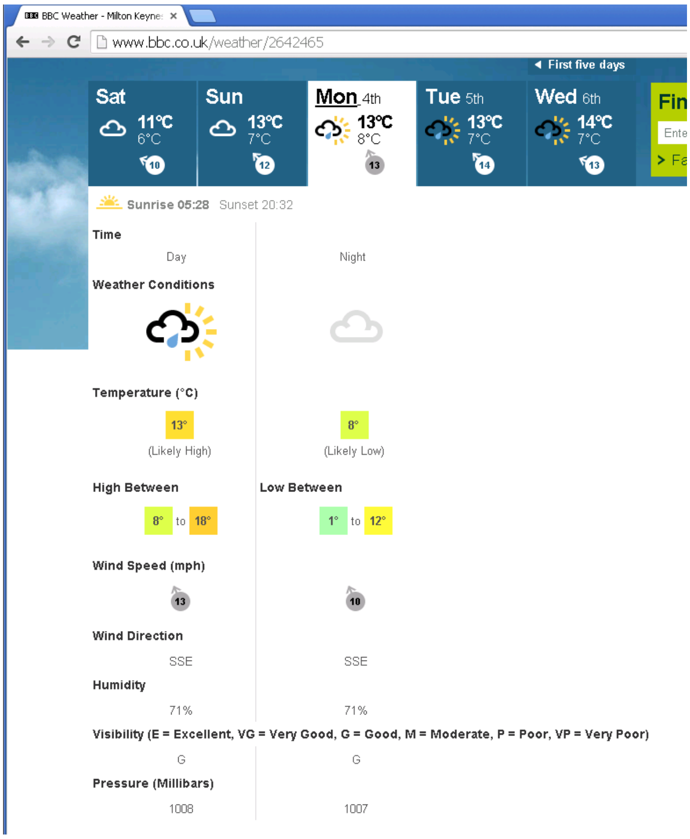


Figure 21 : BBC week ahead weather prediction

LP 23.	Available forecast data is not especially detailed over timescales and requires significant processing to provide time varying shape. More expensive services are available that can be tailored to suit the situation but these come at a cost. A cost benefit analysis between increased confidence in prediction vs cost should be undertaken if predictive DAR OHL is considered.

6.1.3 Data Conditioning

So that the BBC weather prediction data can be used, it was necessary to transform it into the same format as the measured data so that it can be passed through the software model and used to generate predicted results. To achieve this, three forms of conversion were necessary. Firstly, some aspects of the prediction data had to be converted into comparable units (such as BBC wind speed in miles per hour to measured wind speed in metres per second). Secondly, the magnitude of the predicted data was compared to the measured data (for the same timestamp). In some cases, it was found that the average predicted values were higher or lower than average measured values. To adjust for this, a relationship was defined which scaled the predicted data up or down to more accurately reflect the observed data. Finally, since the measured data was collected minutely (and used in the offline models to this level), it was necessary to convert the BBC data to the equivalent temporal format. Where possible, the variation observed in the minutely measured data was used to define a variation rule or probability function that could be used to simulate variation from the predicted data. These three processes are explained schematically in Figure 22.

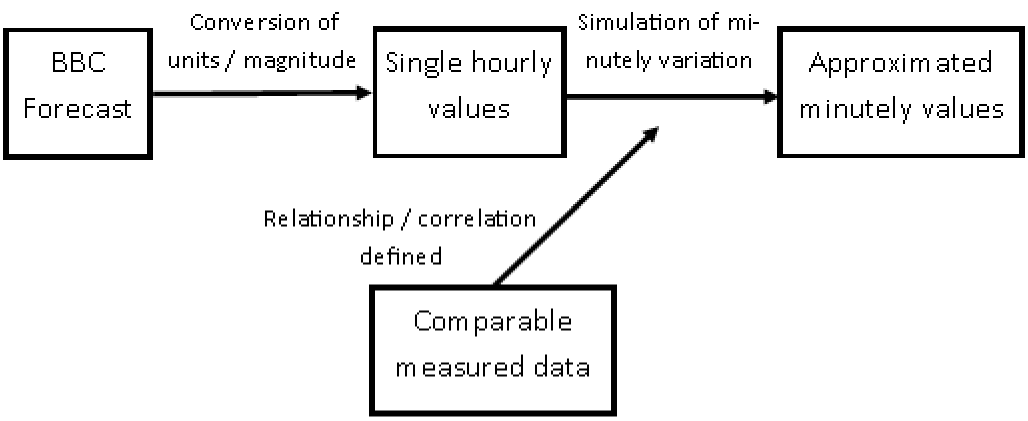


Figure 22 : Forecast data manipulation

Details for the extensive work undertaken to appropriately condition forecast weather data is contained in Appendix E and Appendix F.

The measured data for a sample selection of days across each season and the equivalent day ahead and week ahead prediction of this data is shown in Appendix G to Appendix H respectively.

SECTION 7

Ampacity benefits

7.1 Ampacity results

Figure 23 shows the calculated dynamic rating over the course of the year, using the measured data, in 8 hour fixed sections against the static rating (filtering out any bad data) for feeder 8, feeder 4 and feeder 9 respectively. The data from Figure 23 has been split into a monthly analysis on feeders 8, 4 and 9 as shown in Figure 24. This shows each month with the mean dynamic rating (with error bars showing the maximum and minimum) against the static rating.

At first glance it would appear that all three lines see an 8 hour calculated ampacity benefit which is primarily available from Dec to April and may be quantified at up to 20%.

LP 24.	There are clear areas of significant amounts of time where the dynamic rating is higher than the static rating.

LP 25.	Clear differences can be seen between the dynamic asset ratings of the three lines. This is due to difference in their geographic orientation. Based on prevailing wind directions it can be seen that this favours Feeder 4 ahead of feeders 8 and 9.

This benefit provides no forward indication of what forward ampacity would be and therefore has clear operational limitations, particularly in a planning context and time line.

The project extensively investigated the potential of forecasting forward ampacity as described in Section 6. The results of this for Feeder 8 are shown in Figure 25. Equivalent data for the other feeders is shown in Appendix J.

From Figure 25 it can be seen that the day ahead forecast ampacity is less than the measured 8 hour ampacity, and the week ahead forecast ampacity less again. It can also be seen that the forecast ampacities are reverting back towards the static rating of the line. This should be expected as the ampacity forecasting process introduces a discount of ampacity based on the uncertainty inherent in weather forecasts.

Whilst this investigation of forecasting ampacity provides beneficial learning around the process by which such forecasting can be done. The results indicated for this trial suggest that this forecasting process is unlikely to be able to indicate ampacity benefits above static. However potential improvements in this forecasting process have been identified and it is possible that these may lead to the ability to forecast ampacity that does show a benefit over static rating.

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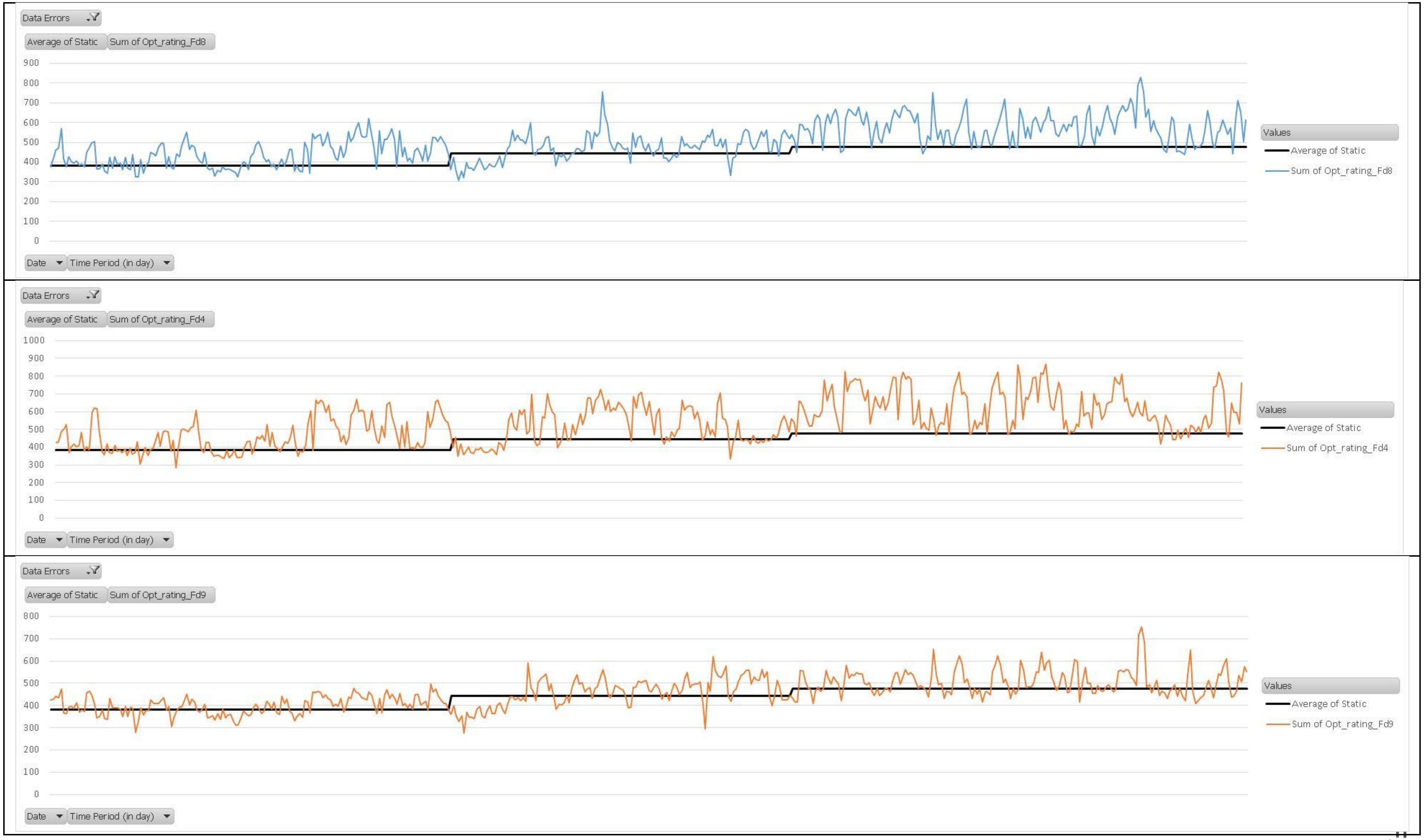

Figure 23 : Calculated ampacity using measured data over the year for feeder 8,4 and 9

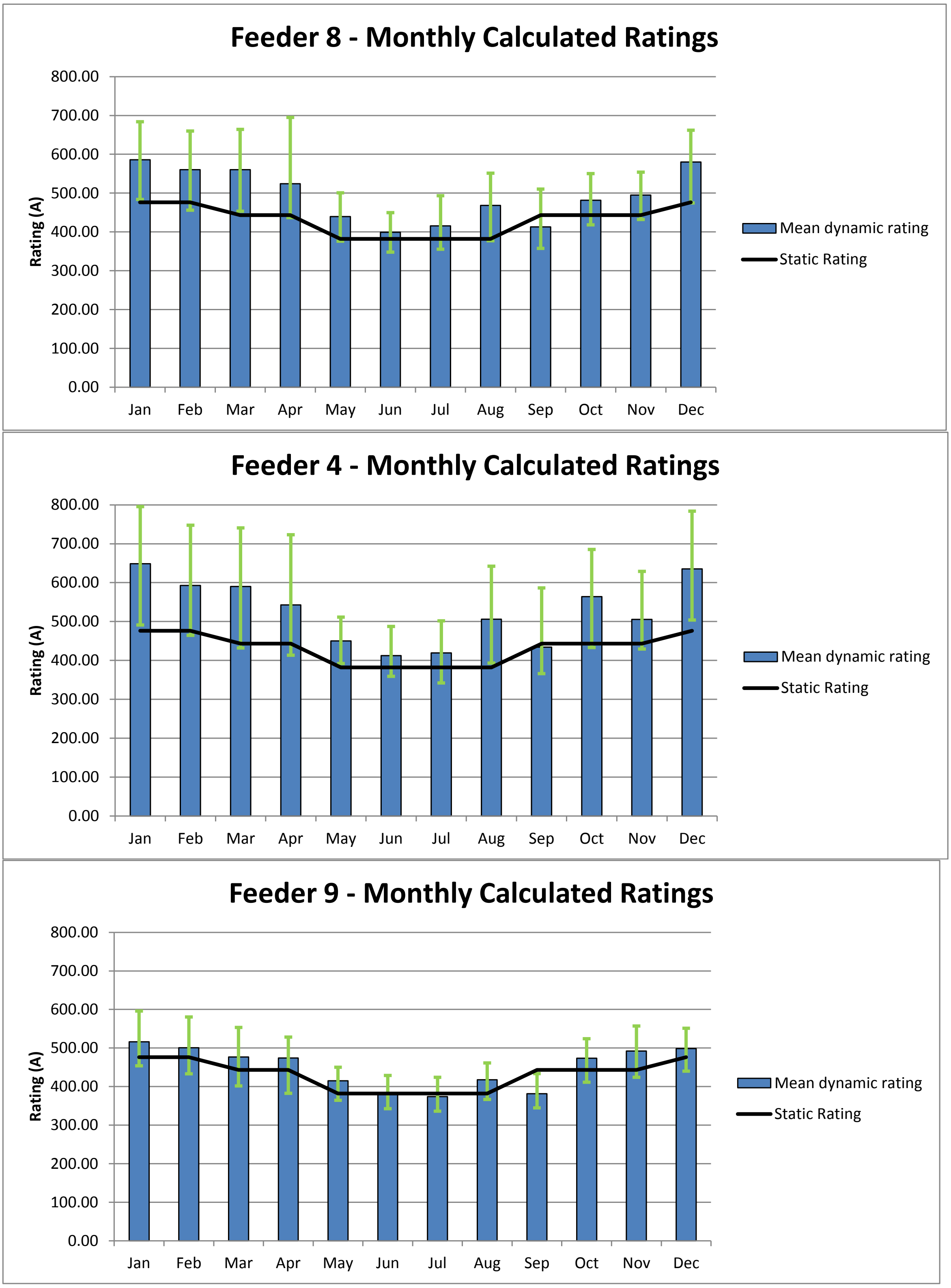

Figure 24 : Calculated Ampacity Benefits using measured data Feeders 8, 4 and 9 over the course of a year

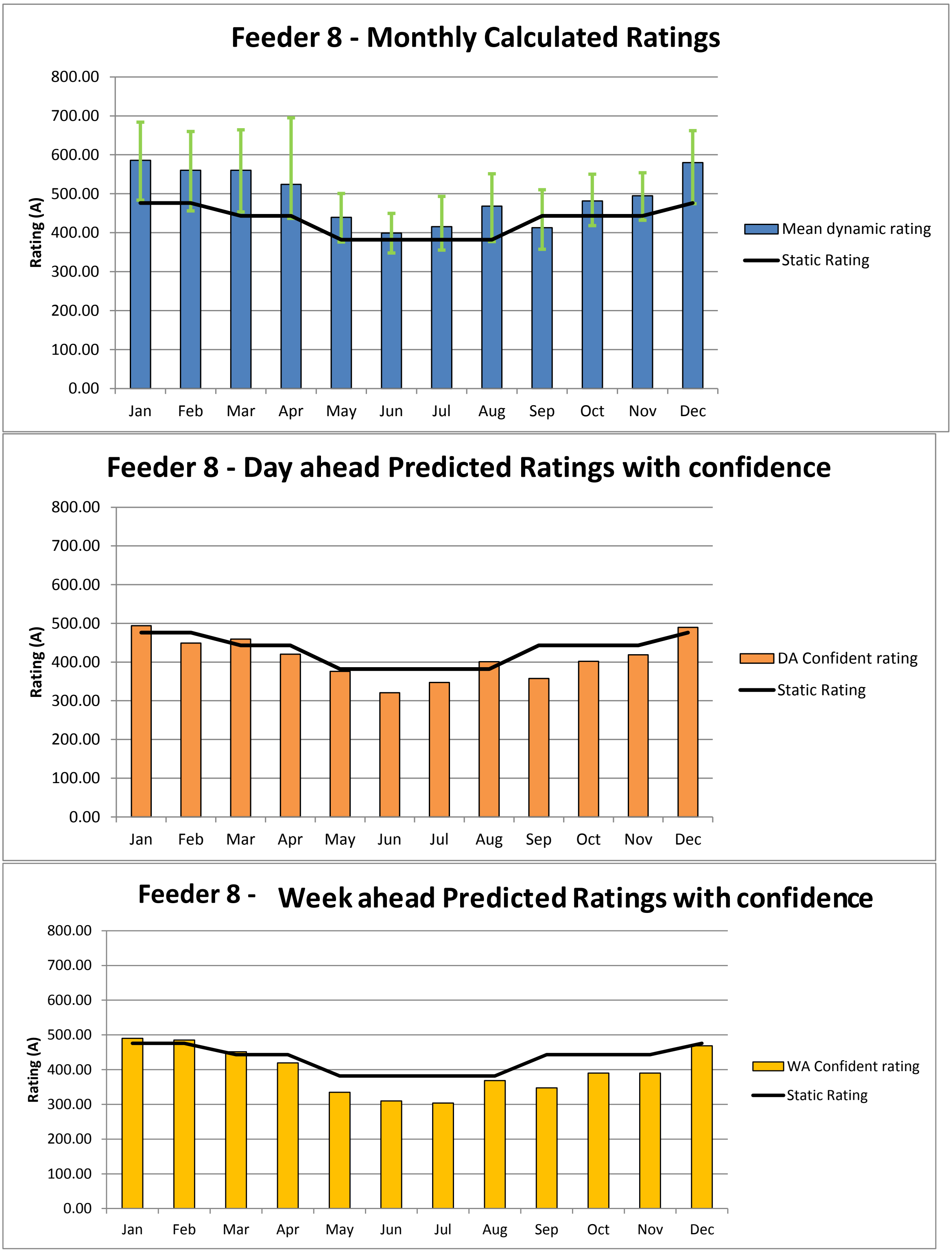

Figure 25 : Calculated Ampacity Benefits using a) measured data b) day ahead predicted data with 90% confidence and c) week ahead predicted data with 90% confidence over the course of a year

OHLs are predominately affected by wind speed/direction meaning significant variations occur both across seasons and within short time scales (minutes). When coupled with the low thermal capacities of OHLs, taking advantage of the benefits this assessment offers is limited to particular circumstances.

Whilst not a direct focus of the FALCON trials, it is clear that DAR systems offer potential benefit to distributed generation. Examples of this include: Increasing export from wind farms on a windy day over OHL. There is less scope to enable solar panels on such a system as the increase in power export would increase with thermal radiation which has a heating effect on the OHL.

It is unlikely that an asset would be run at full dynamic rating under normal operation. It would be much more likely that this usage of the dynamic rating would occur under a planned outage scenario or emergency operation to carry the load when an adjacent circuit is out. As such, the DAR is not likely to have an impact on CI or CML as the planned operation would typically be under the same principle as the current static rating. However, there is increased risk that weather conditions become unfavourable resulting in the need for load reduction on a circuit in the event of unforeseen extended outages.

7.2 Discussion

It is interesting at this point to compare the values that are used in the UK for calculating static rating with other practice (these are mostly at transmission level). In 1998 CIGRE TF 12-1 of SC 22 conducted a survey of line rating practices [26], receiving responses from 71 utilities in 15 countries. Some of the key findings of the survey were:

- About 70% of the responders assumed perpendicular wind speeds of 0.5-0.61m/s. The next most common assumption was 0.9 m/s. There were exceptions, including wind speeds as high as 1.55-2.0 m/s and as low as zero.
- Vast majority of utilities use deterministic ratings. The major exceptions were UK and South Africa who use probabilistic ratings.
- Most utilities use an ambient temperature that is close to the highest expected annual summer temperature. Over one half adjust their ratings seasonally.
- Almost all utilities take solar radiation into account. Typical assumed solar radiation intensities were 1000-1150 W/m^2. A slight majority of the utilities used a relatively low conductor absorptivity of 0.5-0.6. Most of the rest used absorptivities of 0.7-0.9.
- 79% of the responders cited clearances as the main reason for ratings, while annealing was cited as the main reason by 9%.
- Importantly, during the prior 5 years, 51% of the utilities had increased the maximum operating temperature of their transmission lines. 30% had increased their ratings by changing their other rating assumptions.

The advice from CIGRE on real time ratings suggests;

- Monitoring equipment meets the sensitivity, accuracy and calibration requirements.
- It has been verified that the lines which are to be monitored meet the design clearance requirements.
- Monitors are installed in sufficient quantity to provide statistically valid information of the sag or temperature of the monitored circuit.
- The operator can choose between a static and dynamic rating as appropriate.

SECTION 8

Cross-technique Comparison[3]

[3] This section is common to all the engineering technique Final Reports.

Table 5 provides a high level summary of which techniques impact what network metric, with the remainder of the section providing comparison of the DAR Cable technique with other trials, on a network-metric basis.

	DAR - OHL	DAR-Tx	DAR-Cables	ALT	Mesh	Energy Storage
Thermal limits /capacity headroom	✓	✓	✓	✓	~	✓
Voltage limits	No impact	No impact	No impact	✓	~	✓
Fault levels	No impact	No impact	No impact	No impact	×	×
PQ	No impact	No impact	No impact	~	~	✓
Enablement of DG	✓	✓	✓	✓	✓	✓
Losses	×	×	×	✓	✓	×
CI/CMLs	No impact	No impact	No impact	~	~	No impact
Grid/ network services	No impact	No impact	No impact	No impact	No impact	✓
Key: ✓Positive impact; ×negative impact; ~ network dependant, may have positive or negative impact						

Table 5: Cross-technique comparison of impact.

Network capacity:

- All techniques altered capacity on the network;
- DAR evaluates capacity more accurately than static ratings which may suggest additional or in some cases less capacity. OHLs are predominately affected by wind speed/direction meaning significant variations occur both across seasons and within short time scales (minutes). When this variability of rating is combined with the low thermal capacities of OHLs (i.e. the OHL temperatures respond rapidly to the environmental changes), taking advantage of this technique is limited to particular circumstances. The dynamic ratings of both cables and transformers are dependent on ambient temperatures, meaning diurnal (for transformers only) and seasonal variations are clearly present, and the larger associated thermal capacities means short-time duration changes in ambient conditions cause less short term variability in asset ampacity;
- ALT and mesh shift load from one part of a network to another, thereby potentially relieving constraints. ALT offers a far more intuitive mechanism, whilst mesh is continually dynamic by its very nature. The extent to which benefits exist is highly dependent on the connectivity of any candidate network, and loads/generation connected to the network, and the extent to which the loads vary relative to each other; and
- Energy storage shifts load in time, reducing load at a capacity constrained key point in time, only to increase the load at a less critical point in time. The specified power and storage energy capacity clearly need to be appropriately matched to the network load; and adaptive triggering is required to deal with individually daily variations in load, to optimise the impact that the installed system can have on the network.

Energy Storage may complement DAR by providing a mechanism to alter load patterns such that constrained assets might make the best use of available ampacity.

Voltage:

- Three of the techniques offer some potential for benefits (ALT, Mesh, ES);
- ALT demonstrated the largest benefit (4%), on some of the rural circuits that were trialled, but no significant benefit was found on urban circuits;
- Mesh considered a small urban network and for this example there was no significant impact on voltage;
- In general the voltage benefit of the ALT and mesh techniques networks will depend on the voltage difference across pre-existing NOPs, and does not directly address voltage issues at the end of branches
- The installed energy storage systems achieved little impact. In general, the reactive power capacity in relation to the magnitude and power factor of the adjacent load is modest, and can be expected to be expensive to deliver for this benefit alone.

Fault level:

- As is clearly already recognised, introducing generation (including ES) to a network will ordinarily increase fault level, in this instance the ES were small compared to pre-existing fault levels, and so had negligible impact. Meshed networks will also increase fault level due to the reduced circuit impedance. For the mesh technique trial, this was within the ratings of all circuit equipment.

Power Quality (PQ):

- Mesh trials showed no discernible impact on power quality. Super-position theory and the feeding of harmonic loads via different sources means that harmonics presently fed from one source could be fed from two sources (depending on Network impedances), however, it is unlikely that larger scale trials will show any marked appreciable benefits as the majority of loads are within limits defined by standards and as such it will be difficult to differentiate small changes;
- The installed energy storage equipment did not specifically have functionality aimed at improving PQ. At one site, improvement was noted, however this was a beneficial coincidence arising from the nature of a local (within standards) PQ disturbance and the inductance/capacitance smoothing network in the Energy storage system;
- More targeted studies of a network that has a known PQ issue could be identified to further examine the potential of mesh/ALT techniques to beneficially impact this issue.

Enablement of DG:

- This was not specifically studied as part of the engineering trials (e.g. interaction between the engineering techniques and DG was not designed into the trials);
- Whilst not a direct focus of the FALCON trials, it is clear that DAR systems may offer potential benefit to distributed generation, but is highly dependent on circumstances.

For example, OHL DAR can increase export from OH connected wind farms on a windy day; but solar farm output peaks occur on clear summer days when DAR OHL is less likely to provide additional benefit;

- ALT may facilitate the connection of more distributed generation. However, this needs to be looked at on a case-by-case basis as the location of the generation along the feeder, in relation to the ratings and load, can have an impact. Where the generation is close to the source (such as in the FALCON ALT OHL trial), there is scope to add a significant amount of generation so that the feeder is able to export at the Primary and also meet the load requirements along this feeder. The nominal location for the open point may well be different between when the generation is running or is off and this may impact other metrics such as losses and voltage regulation if generation operating condition is not considered.
- Meshing may facilitate the connection of more distributed generation by providing a second export route in certain scenarios, thus saving on line and cable upgrades. Modelling also indicates that there may be cost savings from reductions in feeder losses when meshing a network with DG connected to one feeder. However, the benefits of reduced losses would have to be compared on a case-by-case basis with the costs of more complex protection required for meshing (potentially necessitating replacement of existing protection relays as well as new relays).
- ES systems offer potential benefit to distributed generation. Examples of this include: peak generation lopping - storage of peak energy production (say above connection agreement levels) for later injection to the grid; and storage of energy to allow market arbitrage.

Losses

- As discussed in the preceding technique-trial specific section, ALT and Mesh offer some potential, though the magnitude is network specific.
- The trialled ES systems increased losses, and DAR will tend to increase losses if higher circuit loads are facilitated.

CIs and CMLs

- ALT changes NOP positions and consequently affects numbers of connected customers per feeder. The trial algorithms:
  - Increased one feeder numbers by 15% (whilst optimising capacity headroom) on a rural/OHL network; and
  - Increased one feeder numbers by 50% (whilst optimising losses/voltage) on an urban/cable network.
- Meshing networks does not improve customer security as such; the improvement only occurs if additional automatic sectioning/unitising occurs beyond that offered by the pre-existing NOP. Due to communication system limitations, the implemented trials did not increase the number of sections, essentially maintaining the pre-existing customer security.

Grid/network Services:
Whilst these trials have demonstrated that frequency response is possible with the ES technique, a marketable service is not fully delivered by the installed equipment. In addition, further work would be required to put DNO owned energy storage on an appropriate commercial basis. Refer to the WPD Solar Store NIA project.

http://www.smarternetworks.org/Project.aspx?ProjectID=1671

SECTION 9

Conclusions and recommendations

Overhead line DAR is dependent on thermal models. Models were prepared under this project and good correlation was found between measured and calculated line temperature.

The technique trial identified significant average real time ampacity benefits. However, the ampacity varies over a large range within a very short time frame largely driven by variation in wind speed. This rapid variation in wind speed coupled with the low thermal mass of the asset/ short time constants for changes in temperature means that the asset cannot be loaded and relied upon at these identified enhanced average levels for extended periods of time due to the potential for changes in weather conditions.

The potential for this rapid fluctuation in ampacity led the project to investigate the possibility of using forecast weather to estimate forward ampacity (on a day ahead and week ahead basis). This investigation was conducted to address the issue that modelled ampacity indicates an “of the moment” ampacity but does not address the question of capability of the asset over a forthcoming period e.g. day ahead/week ahead.

The method of estimating forward ampacity within this project, concluded that the calculated forward ampacities tended towards the pre-existing static ratings when due account was taken of uncertainties in weather forecasts.

It is worth noting that comparisons between “of the moment” dynamic asset rating and static ratings for September 2014 suggests that the static rating of this month might be better treated as a summer period rather than an autumn period. Clearly this is based on the evidence of only one September period. It is recommended that this data is reported and examined in line with P27.

Whilst it has been demonstrated that ampacity of 11kV OHLs can be assessed, improvements in ampacity are essentially dependant on wind speed/direction, and cannot be relied upon if reasonable planning certainty of capacity is required. It is recommended that 11kV OHL DAR should not be considered a feasible technique for solving long term 11kV distribution network issues at this time. However, this observed ampacity benefit clearly does have operational benefit in specific contexts e.g. extending ratings of overhead lines associated with wind generation.

Appendices

A References

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B Learning Objectives

	A	B	C
1	A1 - Understand thermal models of assets	B1 - Define the boundaries or limits of safe operation	C1 - Define the effect of ambient temperature on assets
2	A2 - Understand changes in maintenance required for all components	B2 - Define the effect of solar irradiation on different asset types	C2 - Define the effect of wind speed and direction on different asset types
3	A3 - Applications of pre-emptive transformer cooling	B3 - Define the granularity of ampacity values required by control	C3 - Communications template/model for technique
4	A4 - Benefits of using MET office data versus real-time data	B4 - Validity of external data, e.g. MET office and own internal predictions/assumptions	C4 - Applications of forward predictions of ampacity values versus load required
5	A5 - Benefits comparison of sensor types and location of placement	B5 - Template for sensor installation on asset types	C5 - Analysis of relationships between different sensor values
6	A6 - Variability of conditions across an asset/confidence in data obtained	B6 - Analysis of effectiveness of assumptions versus real-time obtained values	C6 - Required post-fault running conditions
7	A7 - Application of short term overload on different asset types	B7 - Running conditions required during adjacent outages	C7 - Analysis of probabilistic and deterministic ratings of lines
8	A8 - Future policy for application of dynamic asset ratings across the network	B8 - Quantification of length of reinforcement deferral after implementation	C8 - Standard technique for retrofitting DAR on each asset class

Note: The Learning Objectives presented above were developed generally for the DAR technique (including transformers and cables). As such, not all of the objectives are directly applicable to Overhead lines.

C Installed Equipment Details

- Online OHL DAR measurement

Alstom P341 DAR relay (model P34131BB6M0710J, running software reference P341____6A_710_E) per monitored OHL, providing real-time calculations of conductor temperature and potential OHL ampacity, communicating via IEC 61850 over IP network with Matrikon IEC61850 OPC server software.

Documentation inserted in separate Appendix File.
Manufacturer's documentation

- Wind speed and direction measurement

Gill Instruments Windsonic wind speed and direction sensor providing 4-20mA output signal fed to the P341 relay

Documentation inserted in separate Appendix File.
Manufacturer's documentation

- Air temperature measurement

PT100 resistance thermometer, with light weight radiation shield, measuring ambient air temperature connected to Alstom iSTAT400 transmitter providing 4-20mA output signal fed to P341 relay.

Documentation inserted in separate Appendix File.
Manufacturer's documentation

- Solar radiation measurement

Kipp & Zonan SP Lite2 silicon pyranometer with PR Electronics 5115A signal calculator (mV to mA) to provide 4-20mA output signal fed to P341 relay

Documentation inserted in separate Appendix File.
Manufacturer's documentation

- Tollgrade LightHouse MV sensors

The Tollgrade Lighthouse Sensors (see Figure XX7) are inductively powered devices that measure current, conductor temperature and electric field strength (proxy for voltage), and signal these values via IEEE 802.11 b/g Wi-Fi to a locally mounted Tollgrade Aggregator. The aggregator is a web-enabled device that manages onward transmission of measured values, analytical and status information from the OHL devices to the LightHouse Sensor Management System (SMS) software running on a Linux-based PC.

Documentation inserted in separate Appendix File.
Manufacturer's documentation

- IEC 61850 OPC server

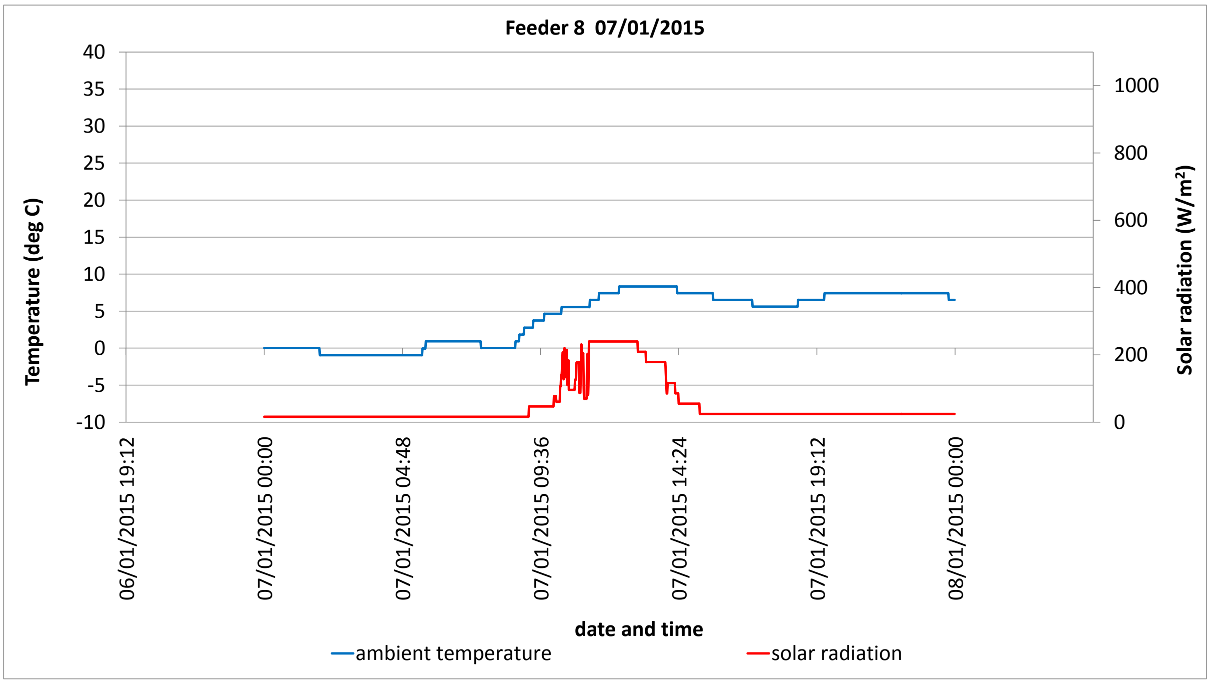
1 pc running Matrikon OPC software suite.

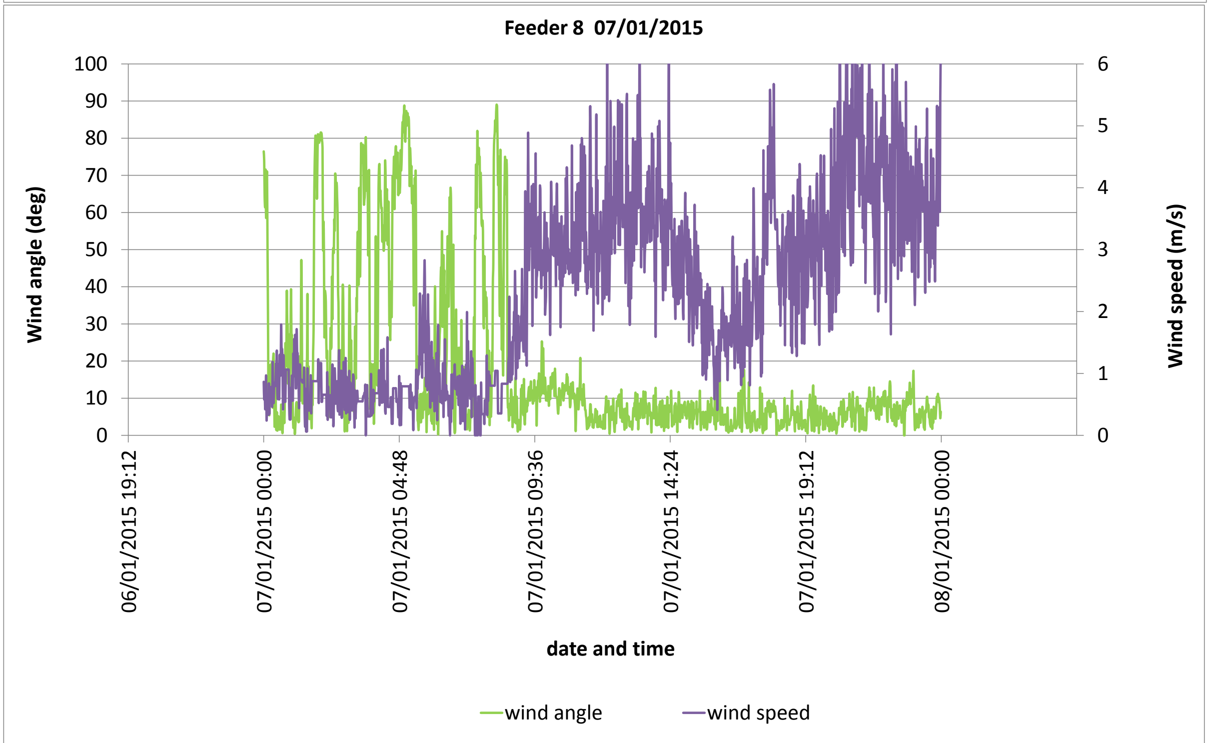
Documentation inserted in separate Appendix File.
Manufacturer's documentation

- As-commissioned DAR drawings for Newport Pagnell

Documentation inserted in separate Appendix File.
Drawings

D Reported measured input data





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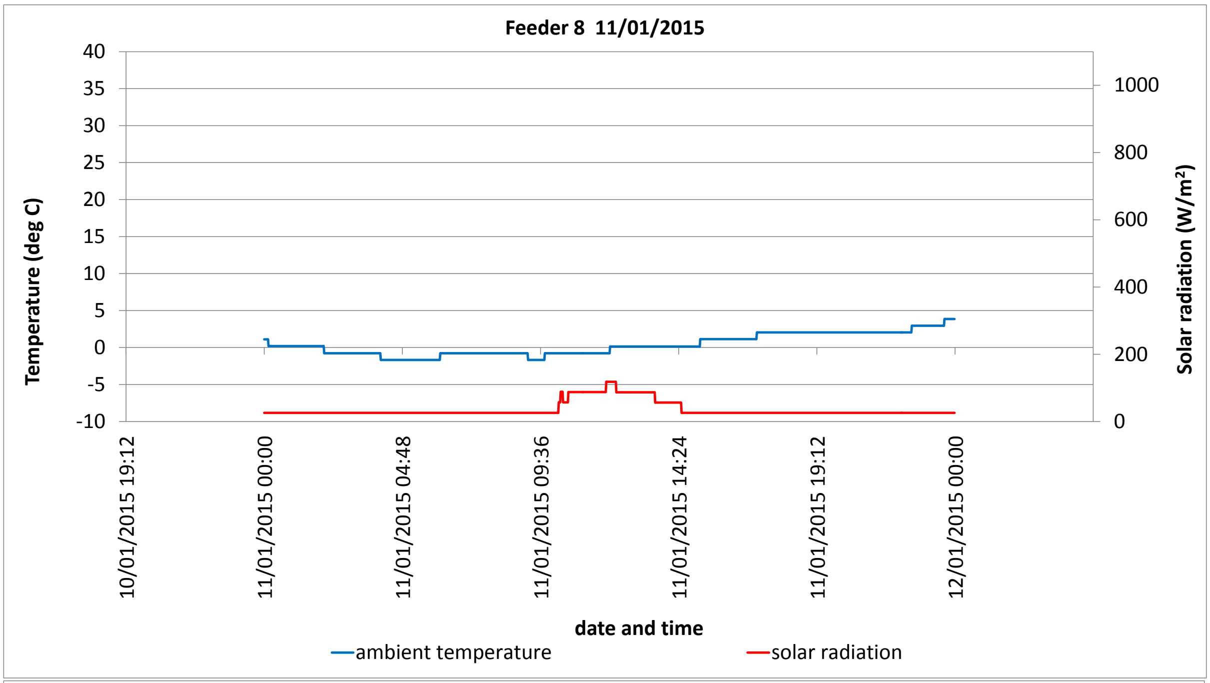

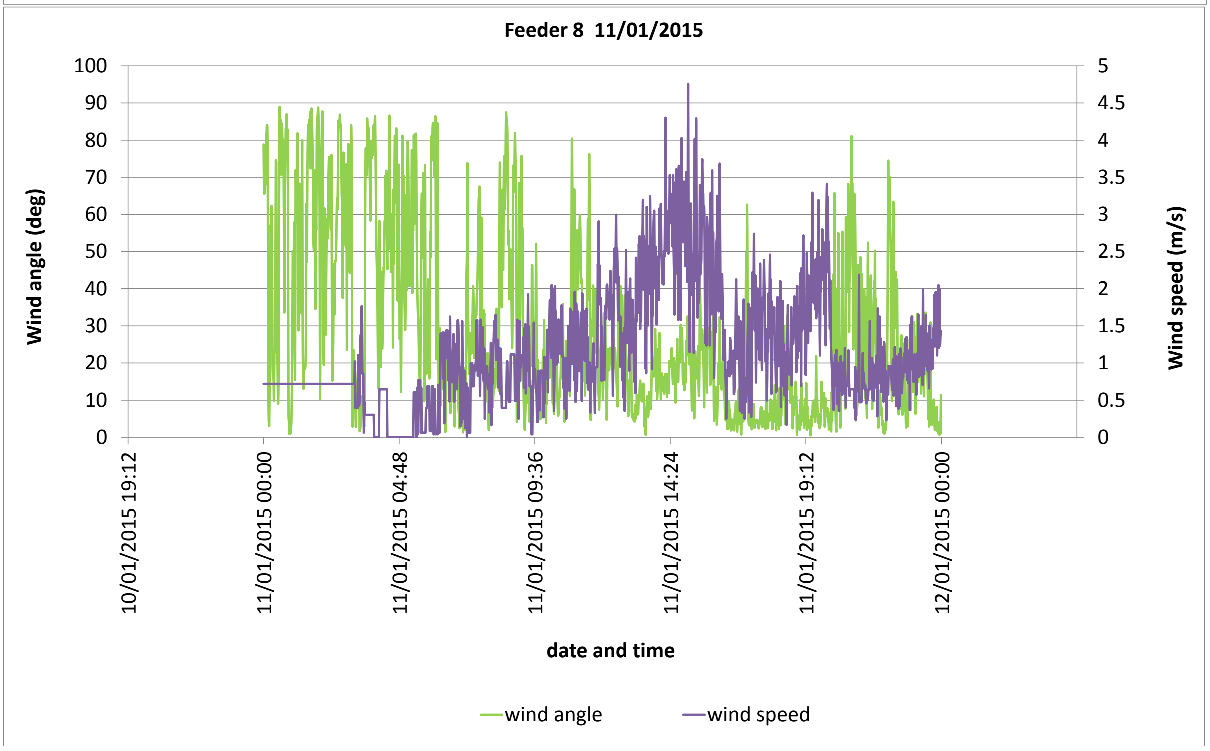

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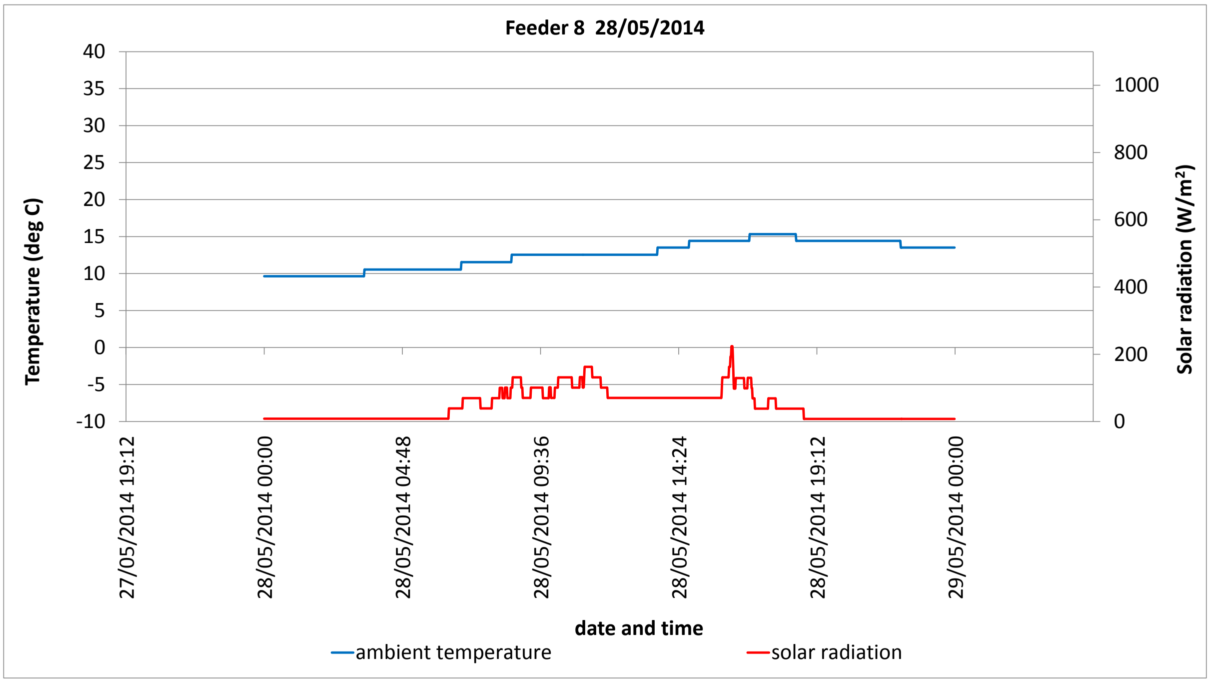

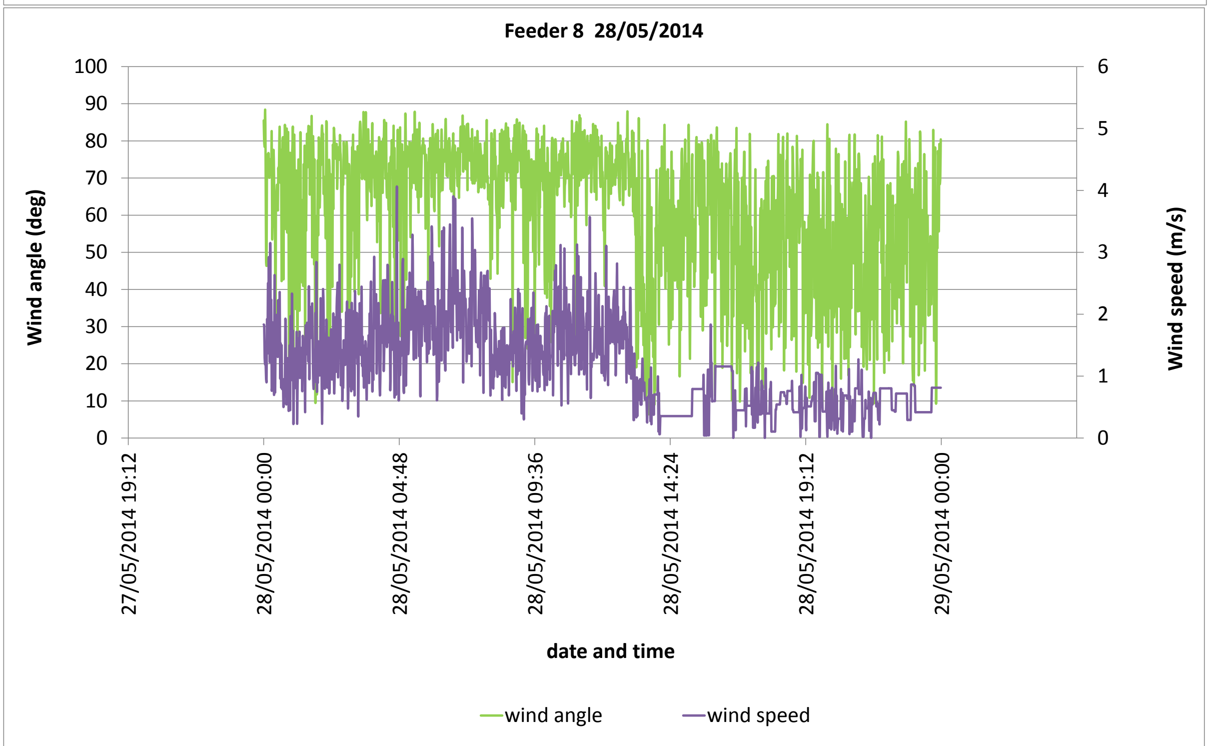

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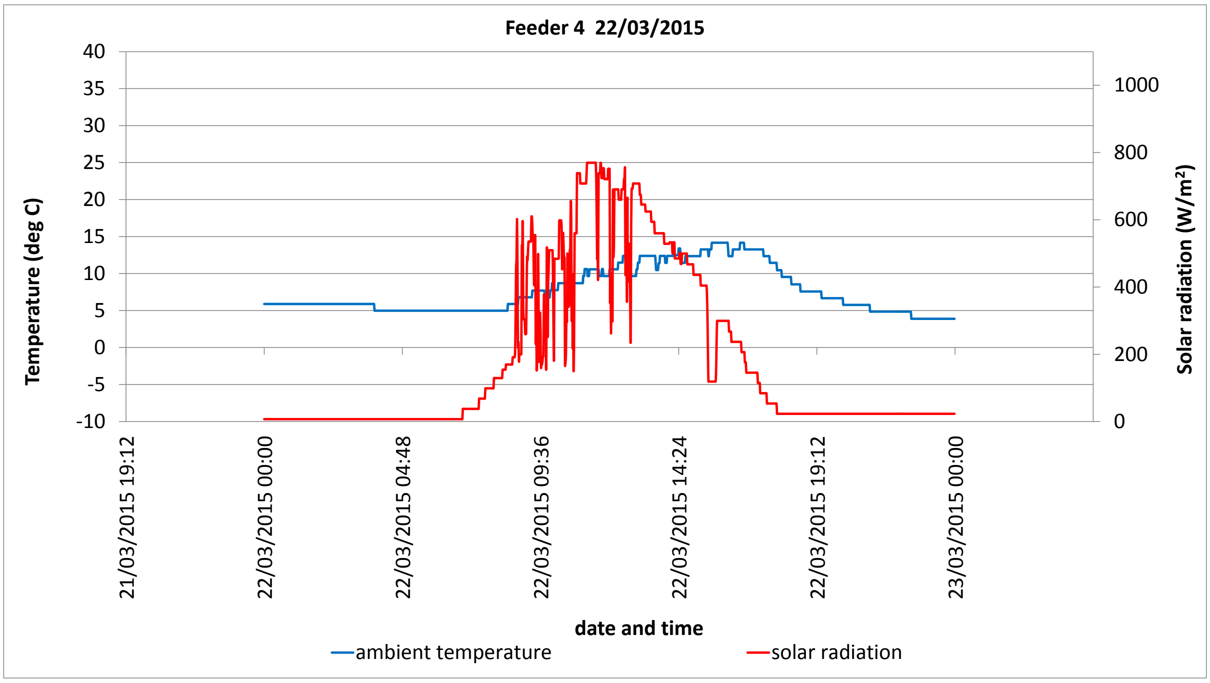

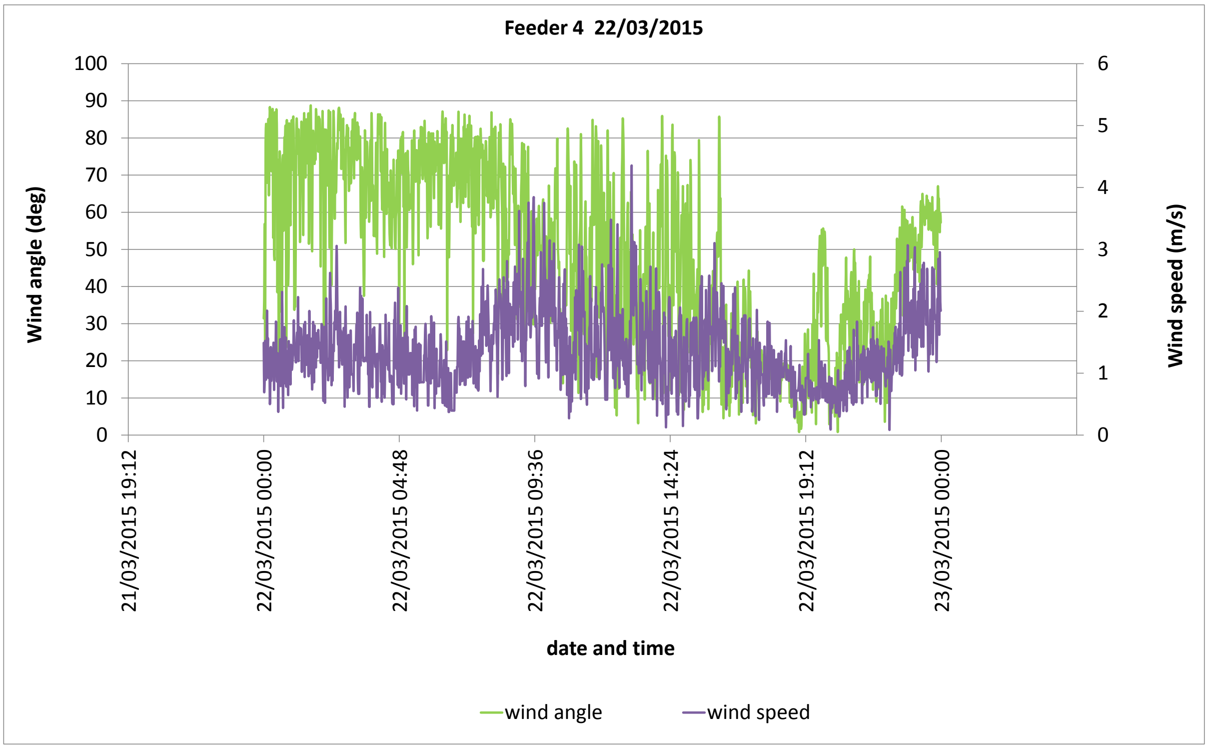

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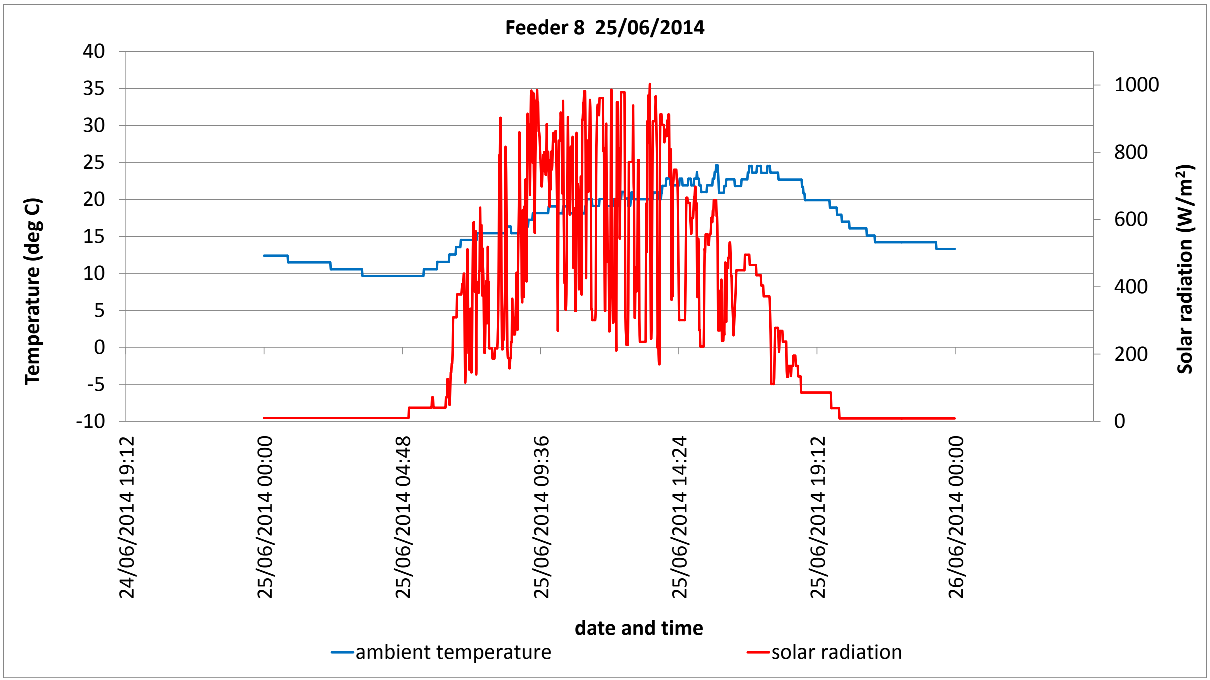

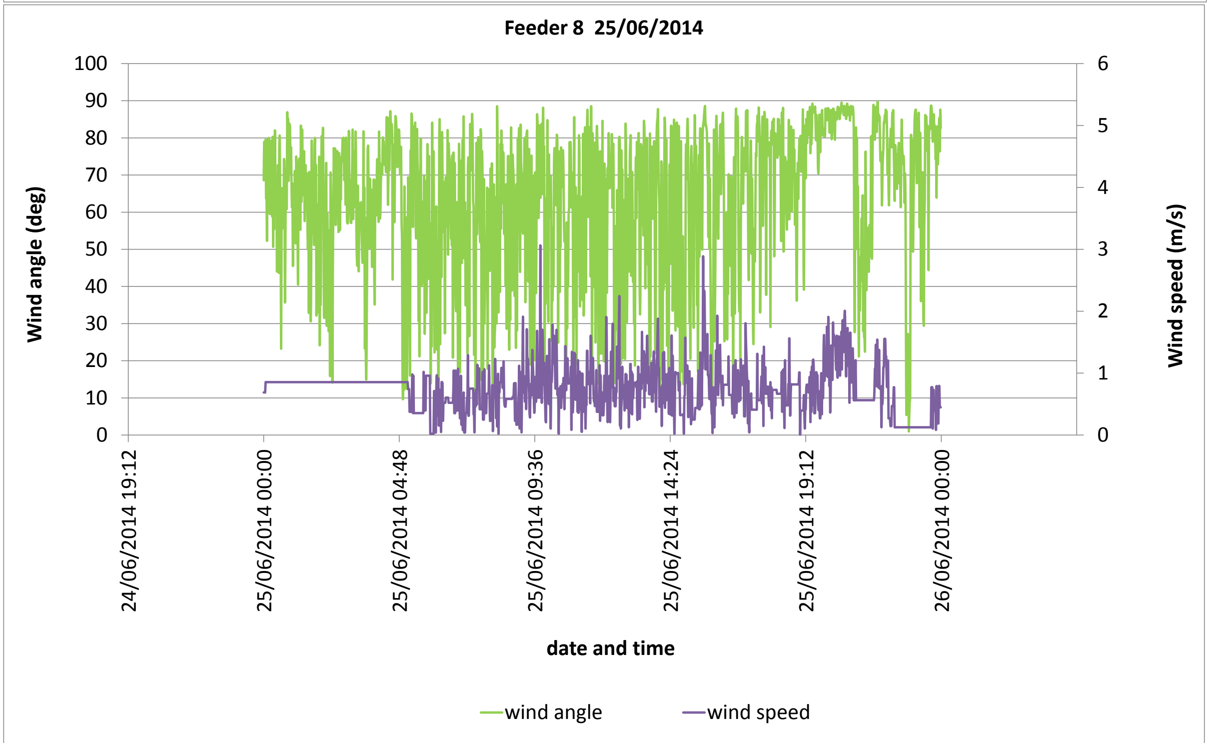

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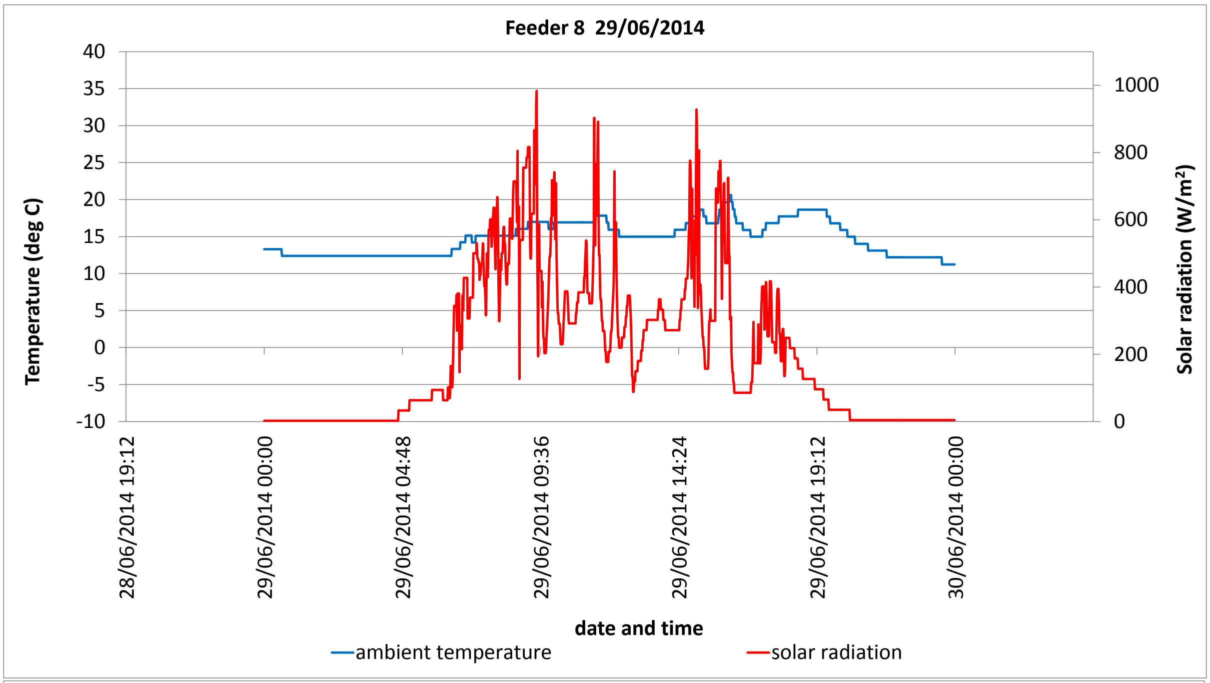

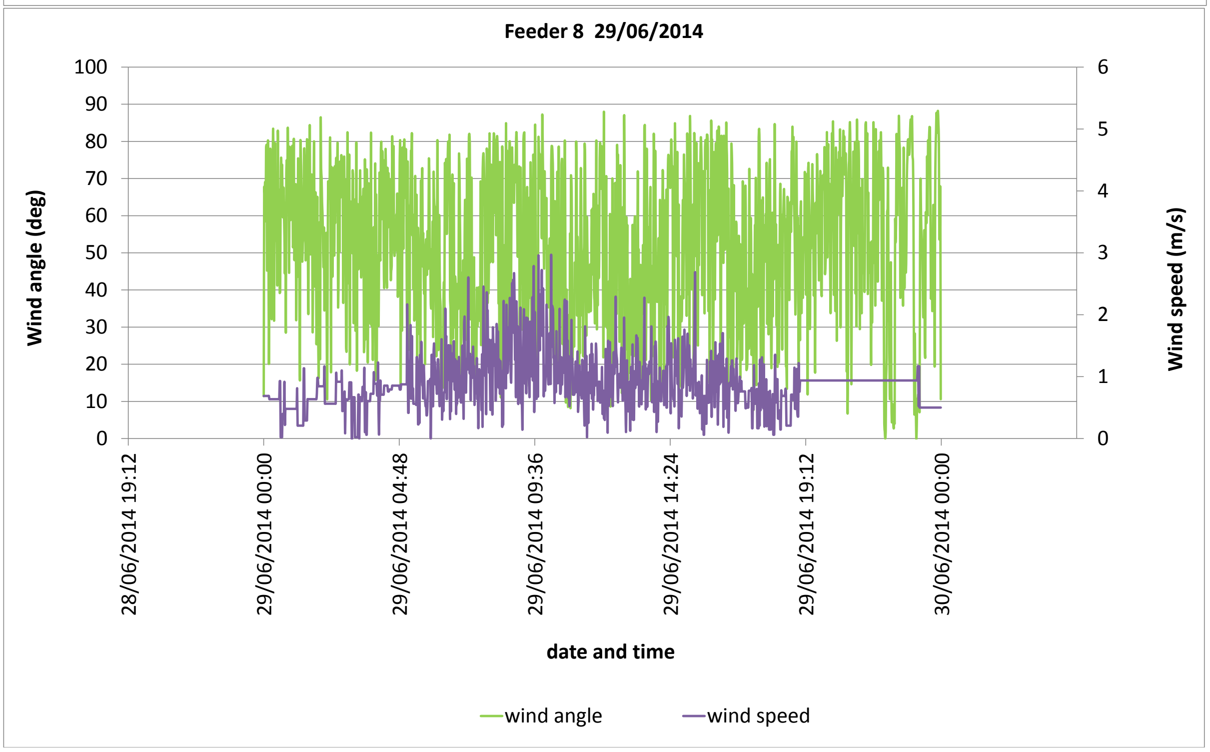

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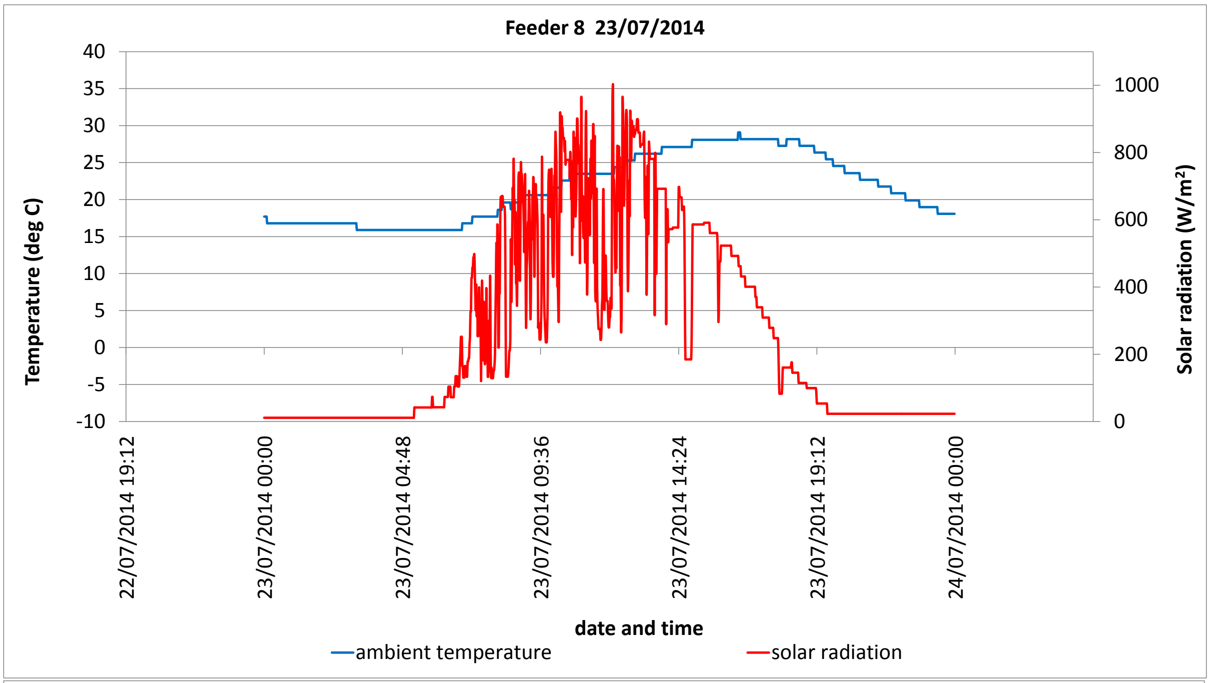

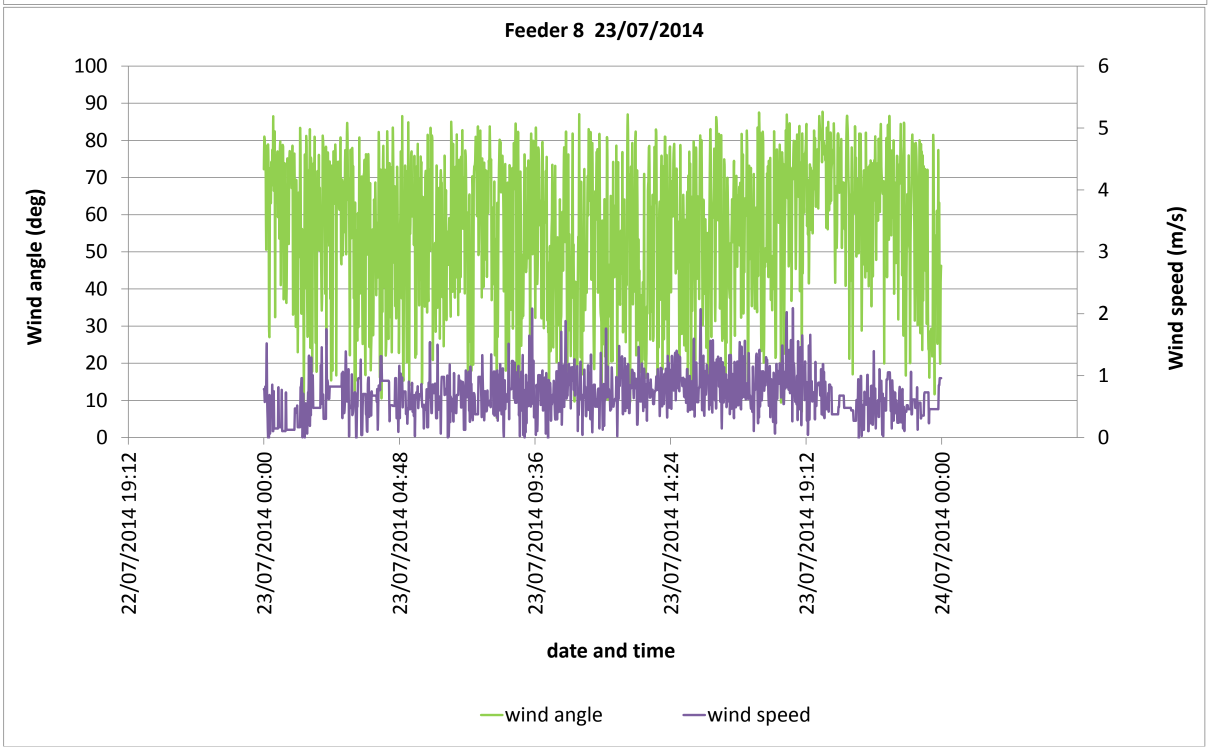

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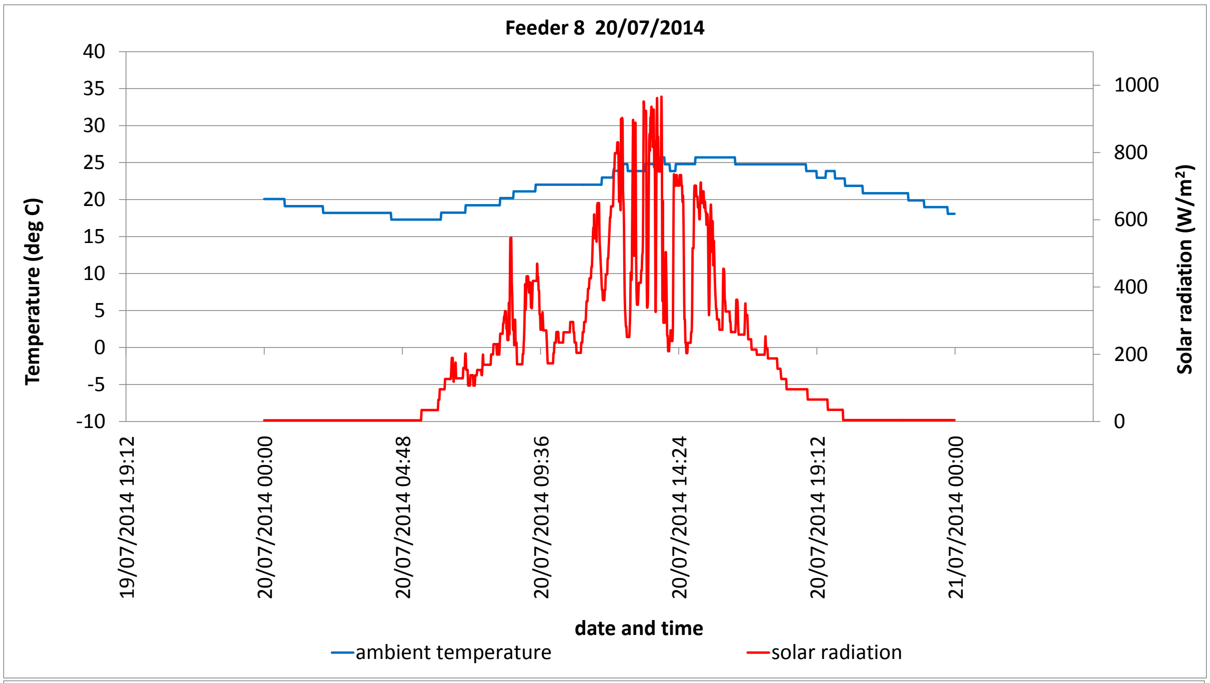

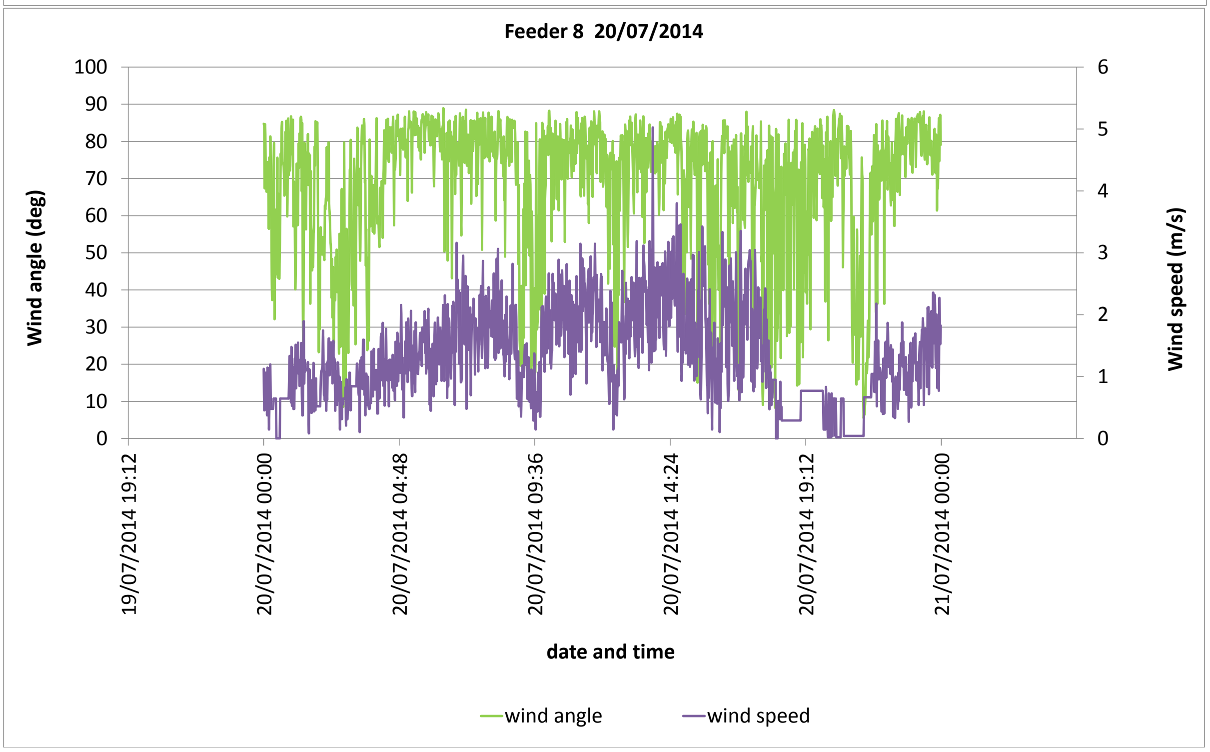

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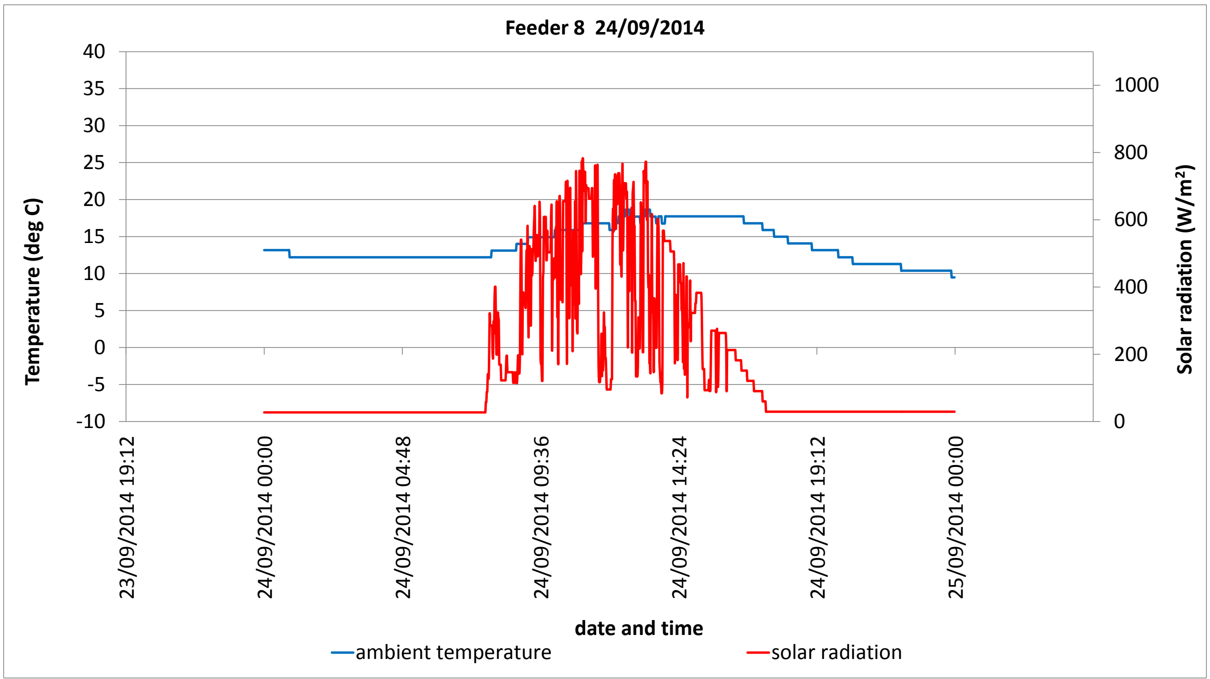
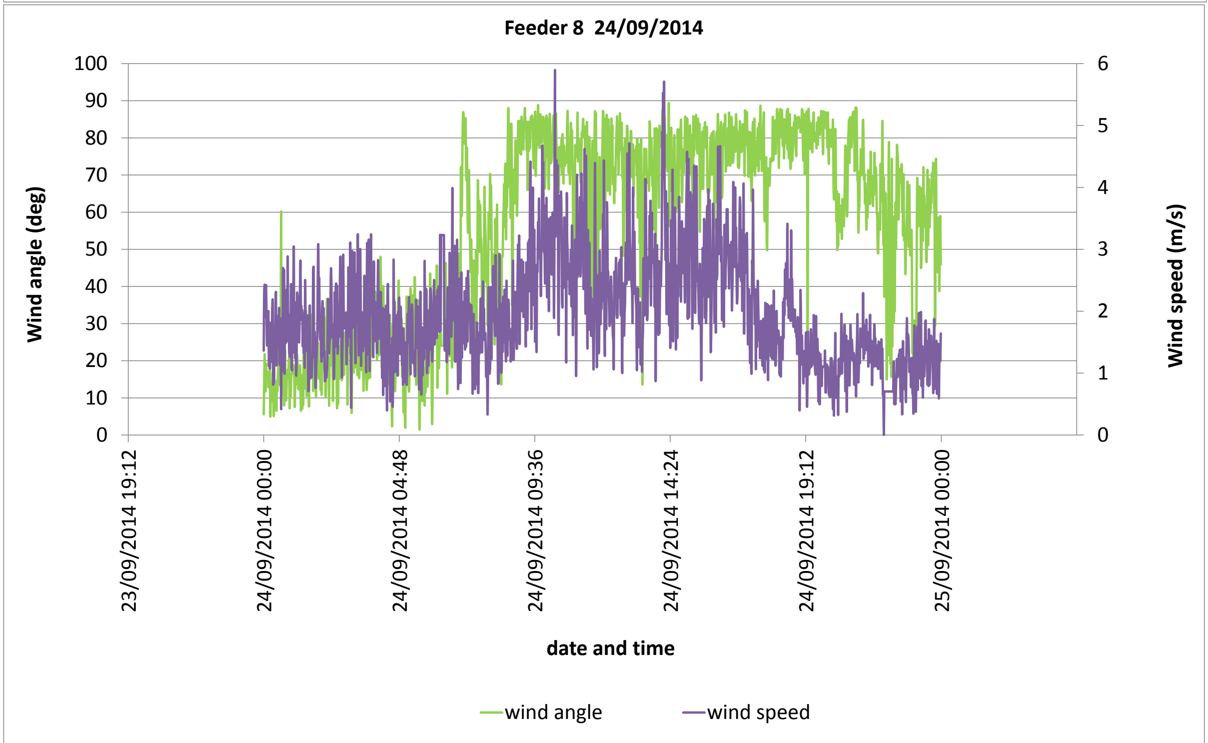
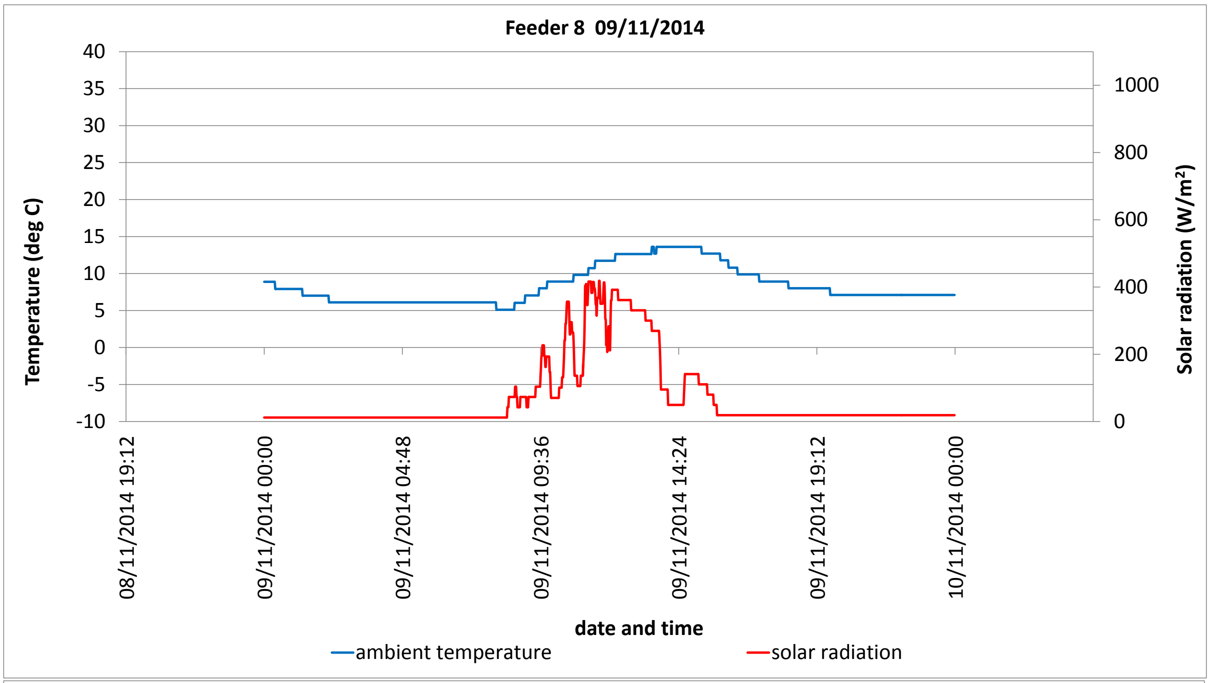
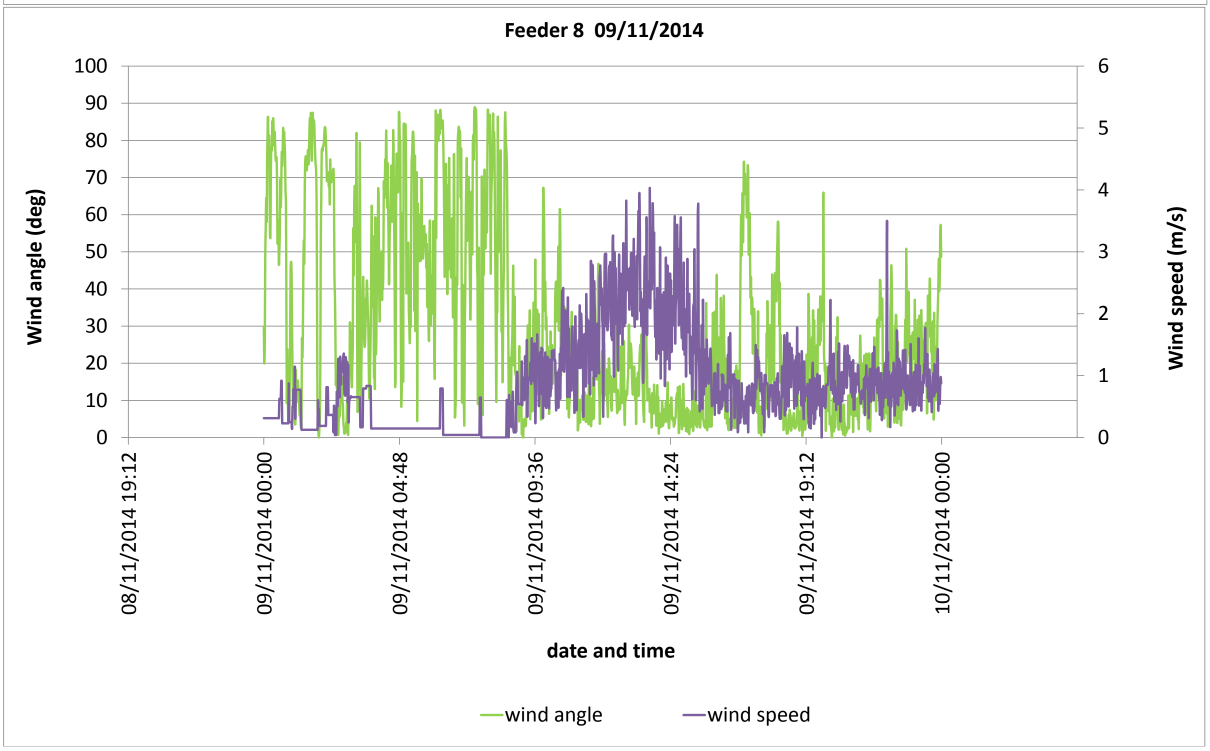




Reported measured data for Autumn Wednesday 24/09/14





Reported measured data for Autumn Sunday 09/11/14

E Formulation of day-ahead data for modelling

The methodology undertaken to look at forecast data is published in more detail in Reference [27]

Day ahead temperature data

The day-ahead BBC temperature data is reported as a fixed value in degrees Celsius for every hour. To convert to minutely data, a linear function is used to approximate the change in temperature across the hour to the next hourly temperature. Thus, minutely temperatures are increased or decreased by 1/60th of the difference between the hourly temperatures. This was preferred to the use of a constant temperature across the hour to avoid sudden jumps in temperature change at the end of the hour.

Day ahead wind speed

The BBC report wind speed in miles per hour (mph) for every hour, whereas the measured data is recorded in metres per second (m/s) every minute. Thus, for the purposes of comparison, the BBC wind speed is converted to m/s using the factor of 0.44704. Despite this conversion, a large difference between the BBC recorded wind speed and the measured wind speed was observed. The primary reason for these differences is thought to be due to the localised conditions where the wind speed was recorded. BBC wind speed data (in collaboration with the Met Office) is recorded 10m above a level surface, clear of objects which may affect airflow. The measured wind speed record is taken at a lower height (to replicate the wind levels at OHL height), and is likely affected by surrounding buildings and trees etc.

LP 26.	Care is needed between assumptions in predicted weather patterns and what would be realistically measured due to geographical situation especially in regard to wind conditions.

A comparison between the two datasets revealed that the predicted BBC wind speed was higher than the recorded measurement. Furthermore, a correlation between the two sets revealed variation between the measured wind speed throughout each hour, and the predicted wind speed (for the same time). The Pearson's correlation, r, was calculated as 0.58 indicating the existence of a positive correlation, but with uncertainty. Given the variability between the two datasets, probability function lookups were generated based on the likelihood of observed differences. Thus for each BBC predicted wind speed value, the proportion of matching measured wind speeds was noted and used to define the probability of these occurring. This is exampled in the table below which shows the cumulative probability of a recorded wind speed being observed when the BBC predicted wind speed is 8mph.

Recorded wind speed likelihood	BBC predicted wind speed mph (m/s)	Recorded wind speed likelihood	
(m/s)	8 (3.57)		
	Cumulative probability		Cumulative probability
0	0.73%	1.35	93.82%

Recorded wind speed likelihood	BBC predicted wind speed mph (m/s)	Recorded wind speed likelihood	
0.05	2.18%	1.45	95.64%
0.15	4.00%	1.55	97.45%
0.25	10.18%	1.65	97.82%
0.35	19.64%	1.75	97.82%
0.45	35.27%	1.85	98.91%
0.55	53.82%	1.95	98.91%
0.65	66.18%	2.05	99.27%
0.75	75.27%	2.15	99.64%
0.85	81.09%	2.25	99.64%
0.95	84.73%	2.35	99.64%
1.05	87.27%	2.45	100.00%
1.15	88.73%	2.55	100.00%
1.25	92.00%	2.65	100.00%

Table 6: Predicted wind speed correlation to measured

The probability lookups for each BBC wind speed (integer values from 0-32mph) are used to infer minutely wind speeds by randomly distributing the expected probability across the hour. Thus, if 5% of recorded wind speeds for a given predicted speed are 1.05m/s, then 3 minutes (5% of 60 minutes) are assigned the value of 1.05m/s.

Day ahead wind direction

The BBC wind angle is adjusted to a bearing using the following look up table. This is then related to wind angle (i.e. angle that the wind hits the line) by looking at the difference between the wind direction and the angle that the OHLs leave the substation (where the measuring devices are located).

BBC direction	Angle
N	0
NNE	22.5
NE	45
ENE	67.5
E	90
ESE	112.5
SE	135
SSE	157.5
S	180
SSW	202.5
SW	225
WSW	247.5
W	270

BBC direction	Angle
WNW	292.5
NW	315
NNW	337.5

Table 7: Wind direction conversion

The angle of the lines was found by looking at an overhead image and comparing to data provided by WPD. The following values were used:

- Feeder 4 – 134^o
- Feeder 8 – 14^o
- Feeder 9 – 31^o

These values were then subtracted from the bearing to provide the resultant wind angle that is relative to each line. Thus, a predicted wind from the East (E) is calculated as having a relative wind angle of 76^o to feeder 8 (90^o – 14^o).

Similar to the wind speed, variation between the minutely observed and hourly predicted data (with the same hour timestamp) was noticeable. This variation was defined by a standard deviation (within each hour) of 15^o. As such, to convert from hourly wind direction values to minutely, the hourly data was varied according to a normal distribution with a standard deviation of 15 for each minute value – and these data were assigned randomly throughout the hour (no discernible pattern was identified for minute-to-minute change).

Day ahead solar radiation

Based on comparison with measured data – the following lookup table was used to convert conditions to a value of solar radiation. This was then multiplied by a solar radiation factor depending on time of day and day of the year. To convert this from a value to a minute by minute variation

Conditions	Solar rad
Light Cloud	500
Partly Cloudy	750
Sunny Intervals	900
--	25
Heavy Rain	250
Light Rain	500
Light Rain Shower	600
Clear Sky	1000
Sunny	1000
Thick Cloud	250
Fog	250
Mist	250
Drizzle	500

Conditions	Solar rad
Heavy Rain Shower	500
Thunderstorm	250
Thundery Shower	250
Table 8: Weather to solar radiation conversion	

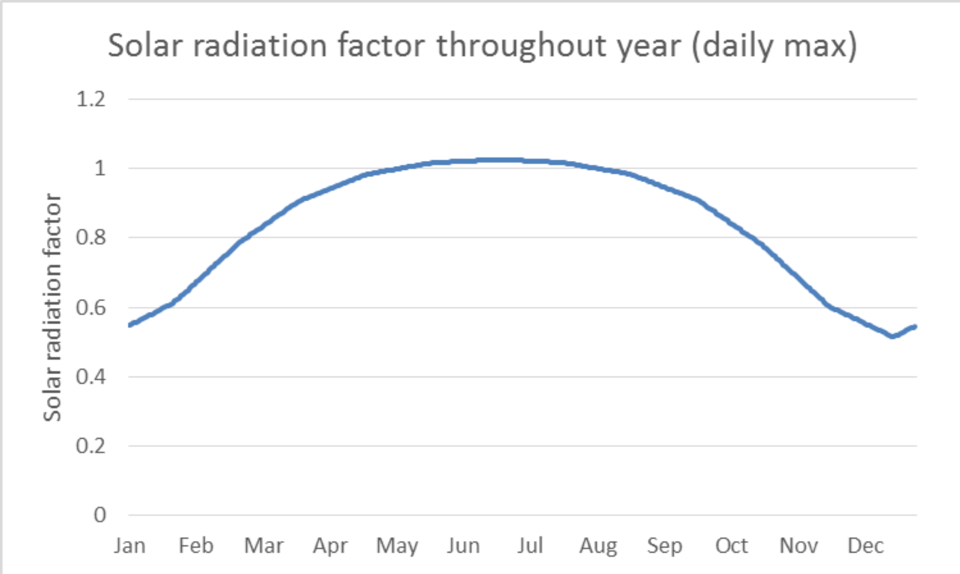


Figure 26 : Variation of solar radiation factor over the course of the year showing main envelope

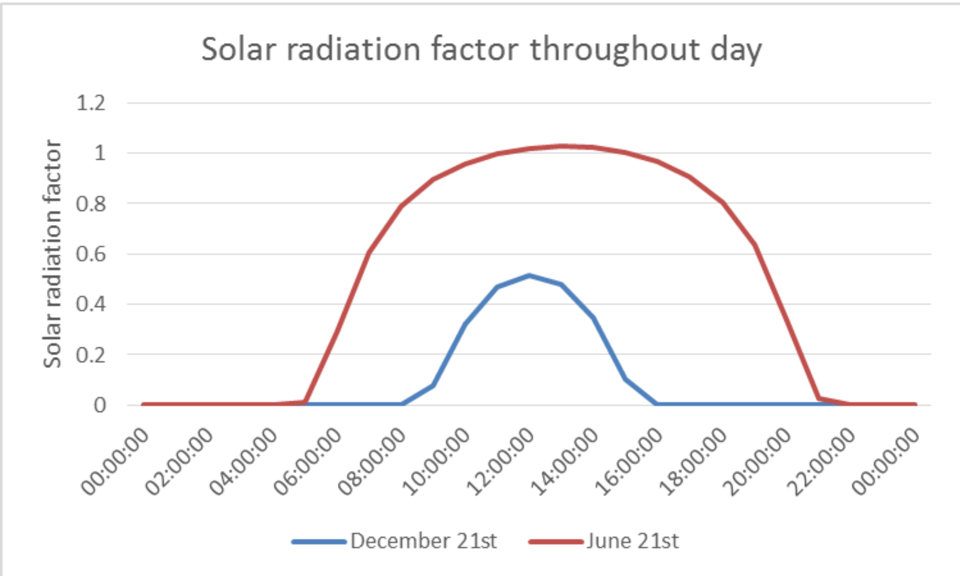


Figure 27 : Solar radiation factor for the first two days in January showing time dependence

Where there is cloud cover, a look up table generates a drop in solar radiation which is then randomised to simulate the effect of clouds passing.

F Formulation of week-ahead data for modelling

Week ahead temperature

Based on a paper by D. H. C. Chow and G. J. Levermore, ‘New algorithm for generating hourly temperature values using daily maximum, minimum and average values from climate models’, Build. Serv. Eng. Res. Technol,,2007., vol. 28, no. 3, pp. 237–248.. The maximum and minimum temperatures are plotted as a quarter sine wave between the two values.

Week ahead wind speed

The two wind speeds are converted into a day and night-time wind speed and then randomised as per the day ahead forecast. In this context night hours are treated as (11pm to 6am).

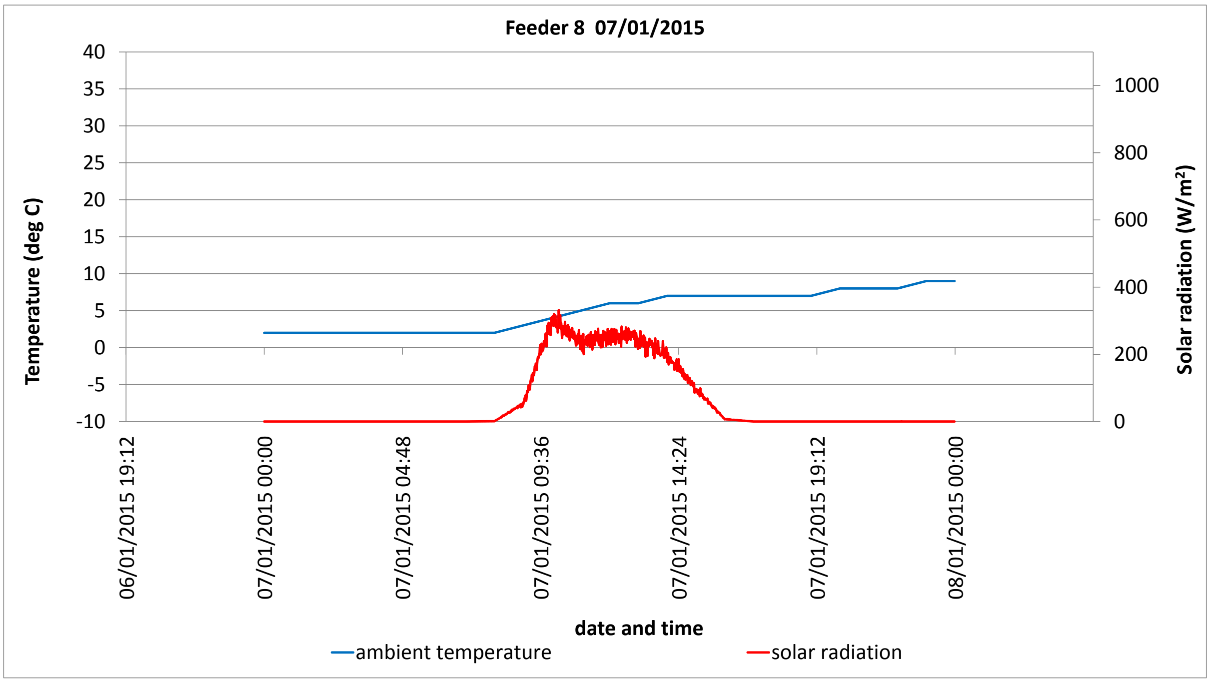
Week ahead wind direction

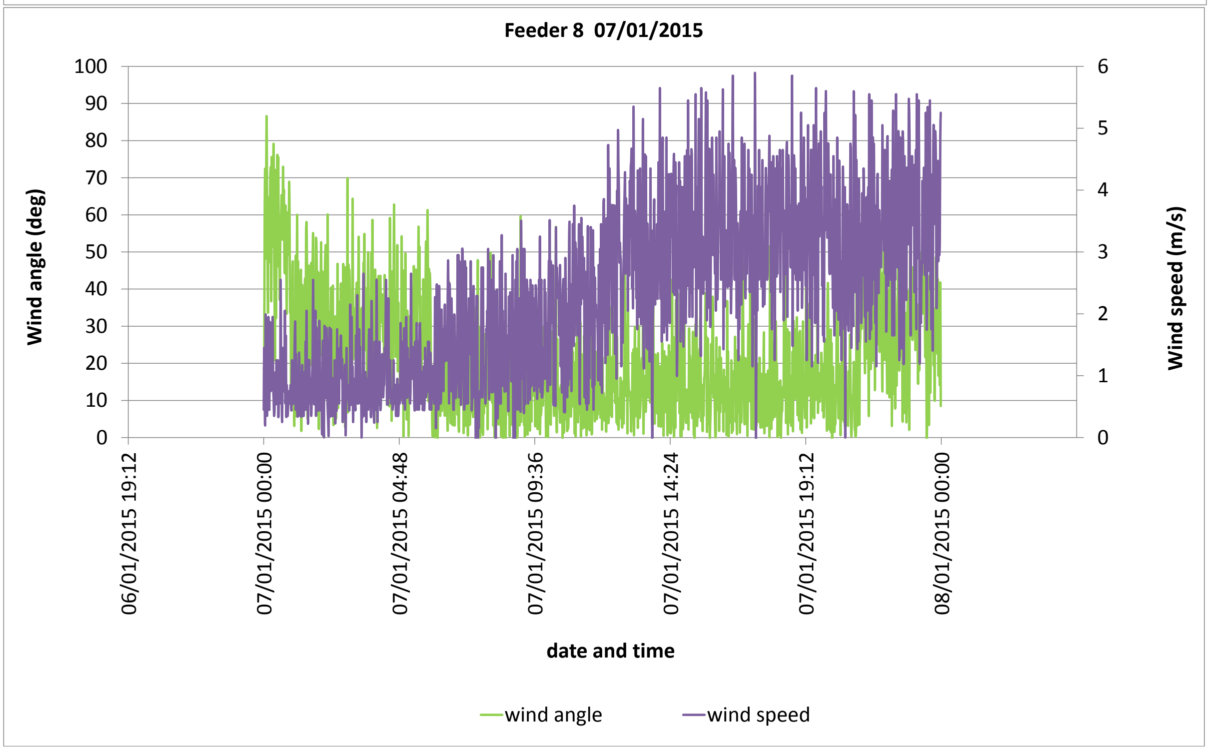
Similar to the wind speed – the two values are randomised over the day and night time values.

Week ahead solar radiation

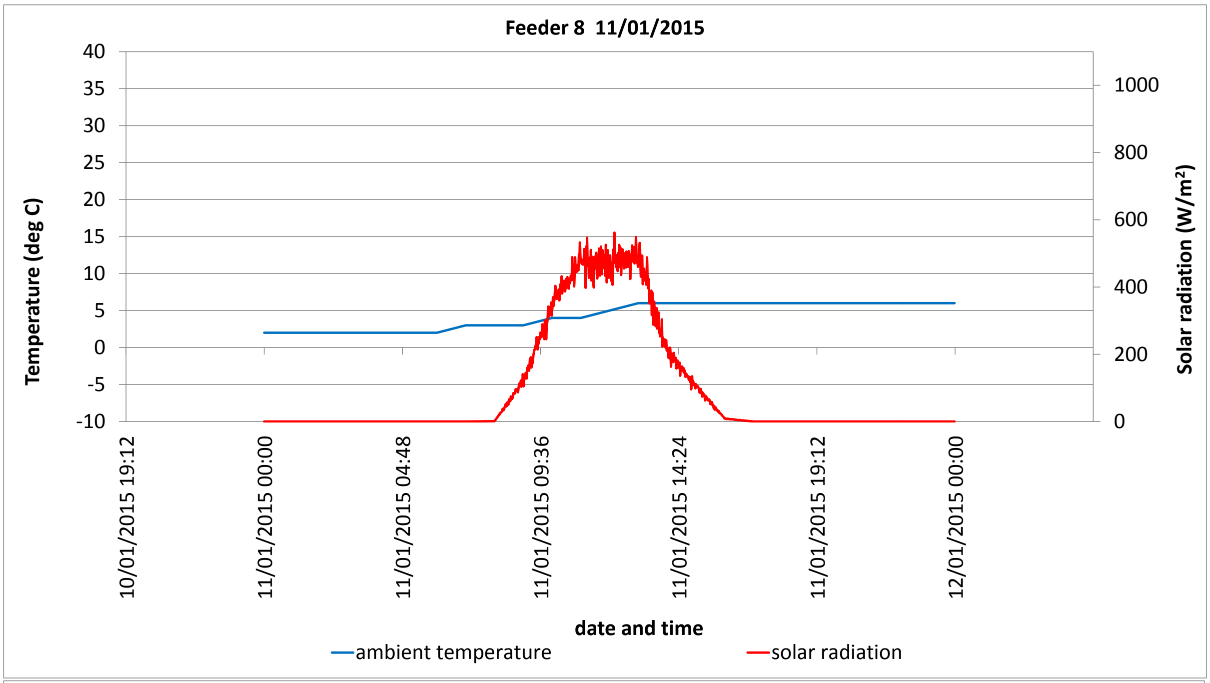
The same lookup table is used as for the day ahead forecast, with cloud cover treated in the same way.

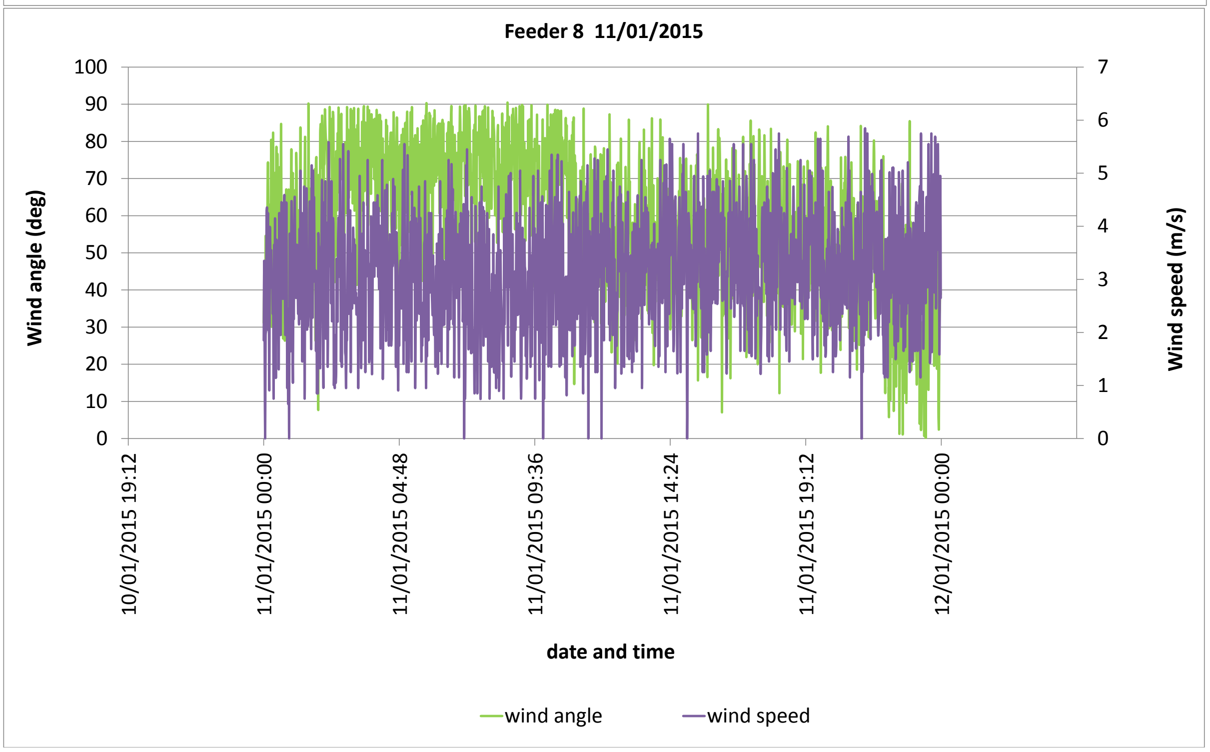
G Day ahead predicted data



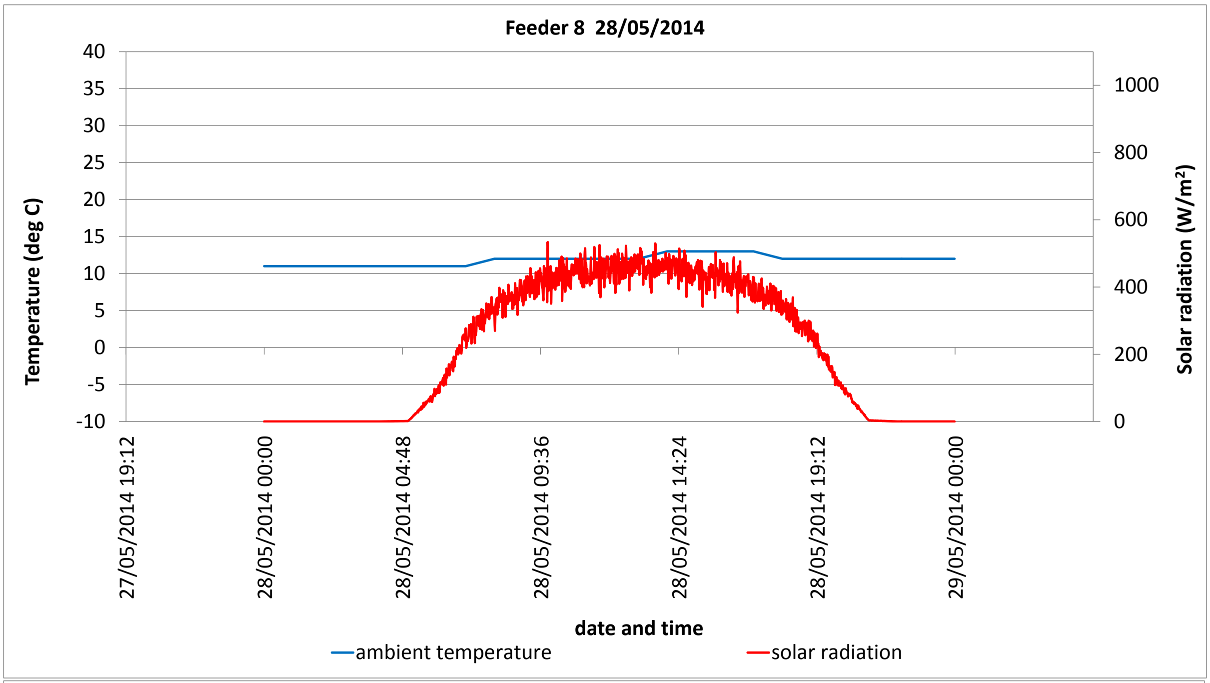


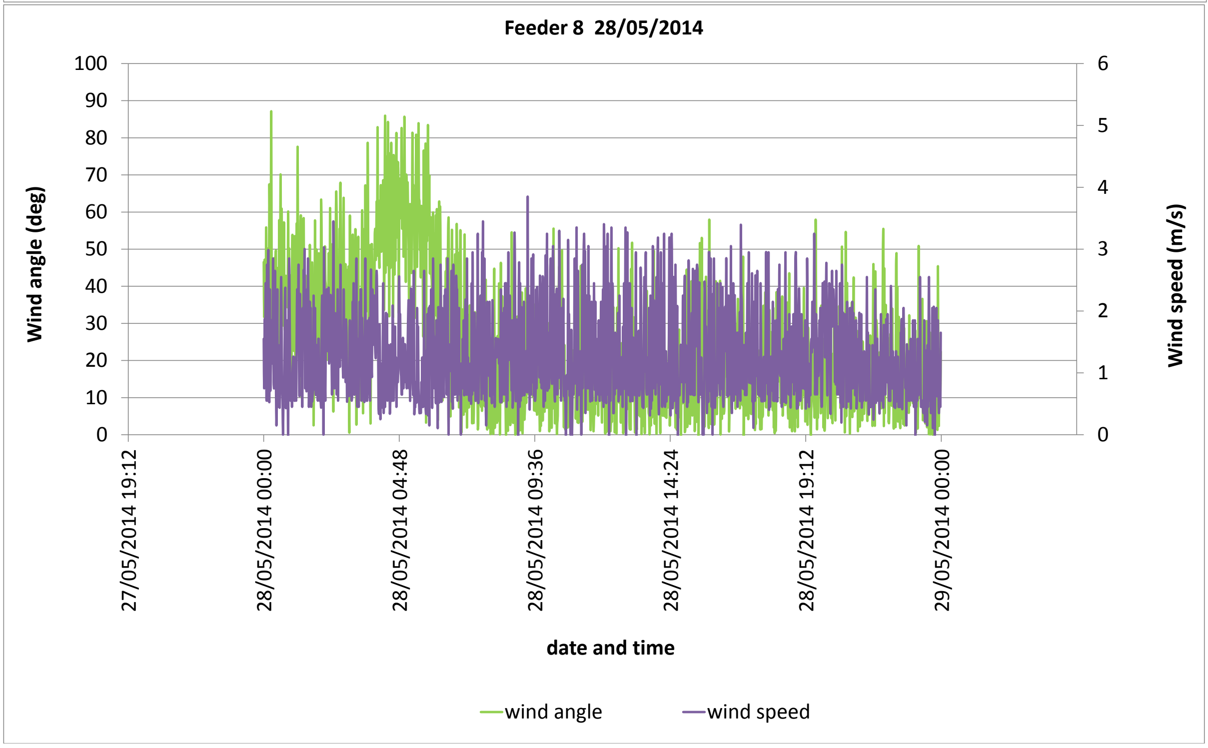
Day ahead predicted data for Winter Wednesday 07/01/15



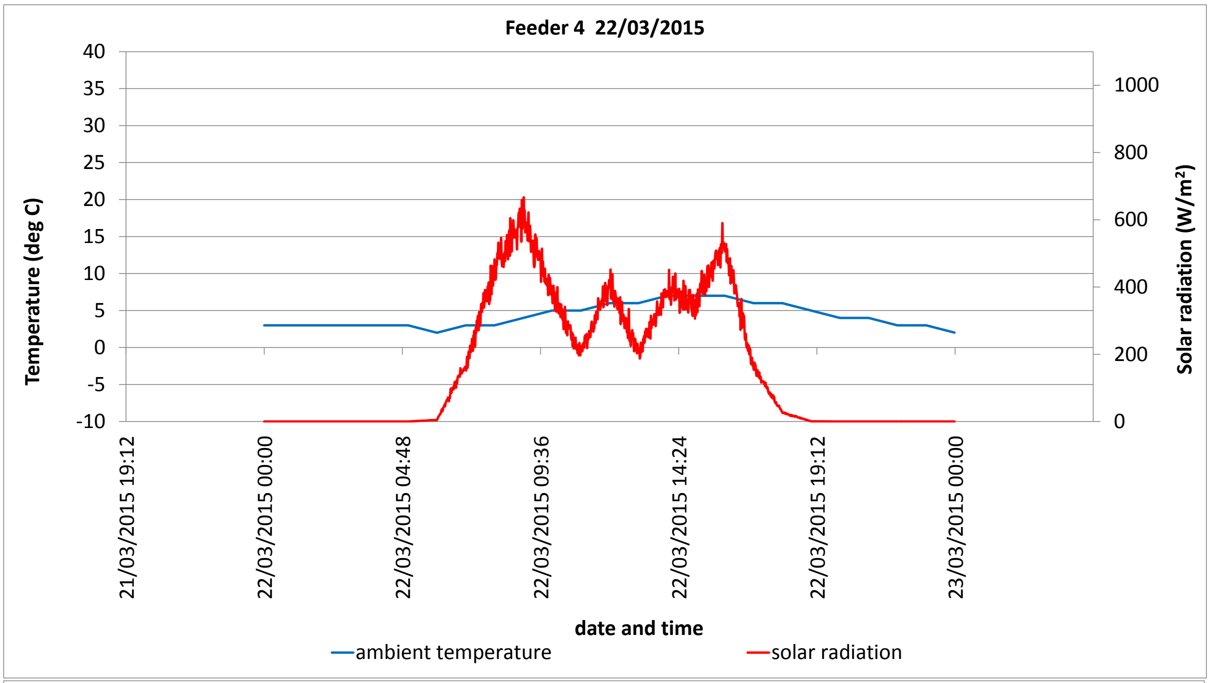


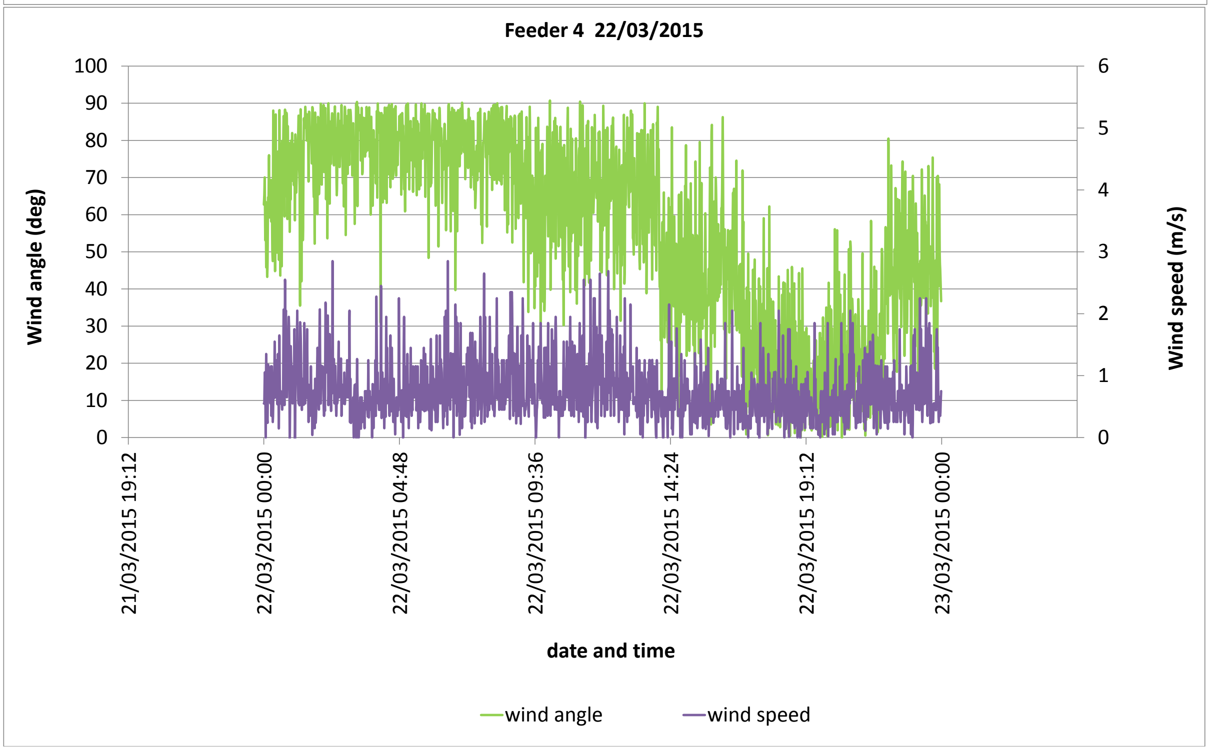
Day ahead predicted data for Winter Sunday 11/01/15



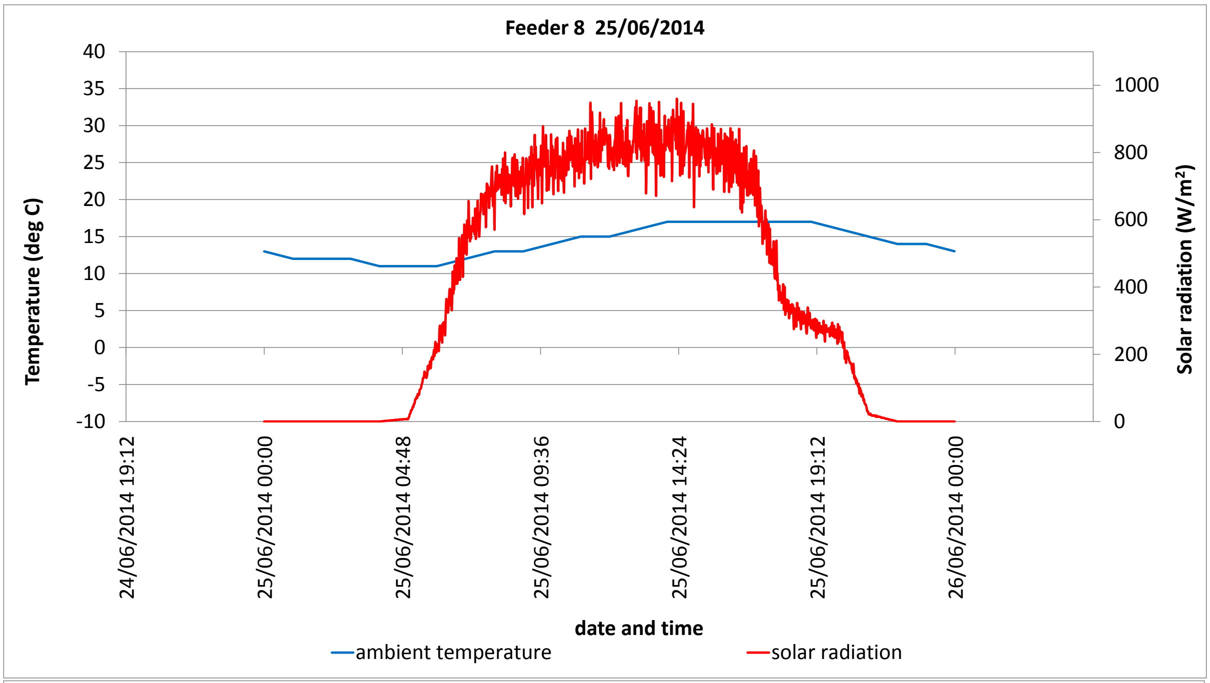


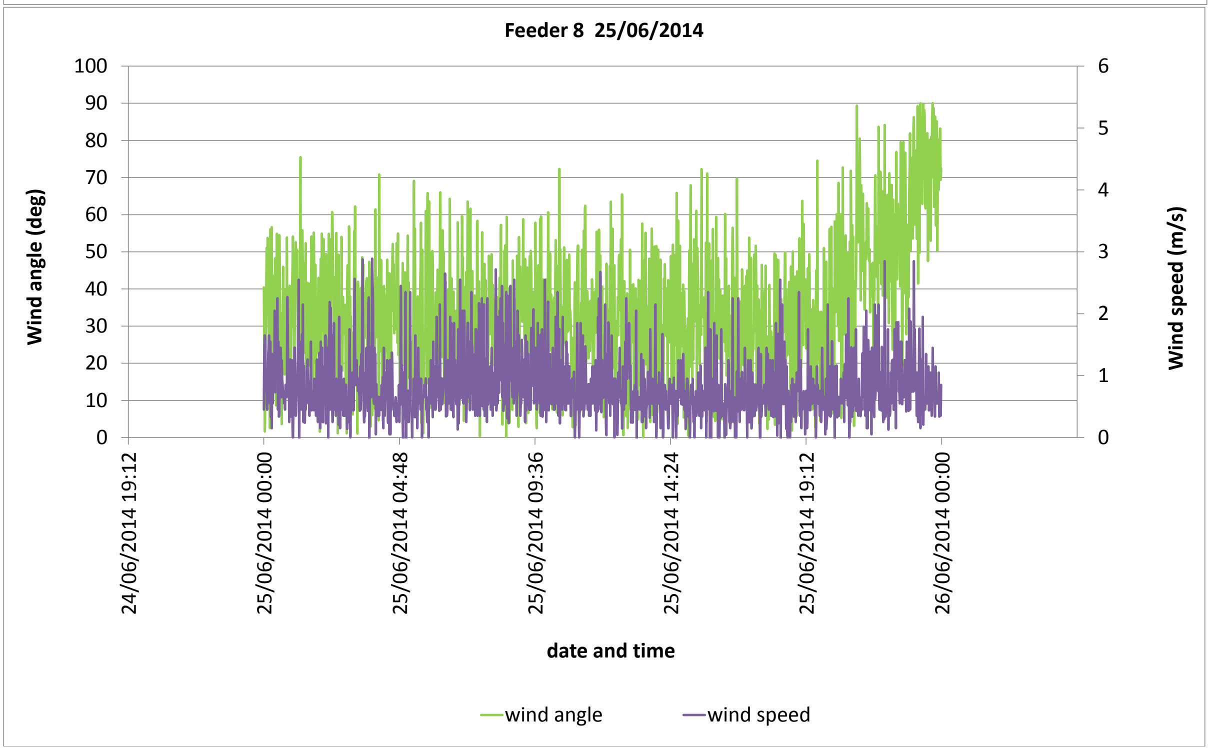
Day ahead predicted data for Spring Wednesday 28/05/14



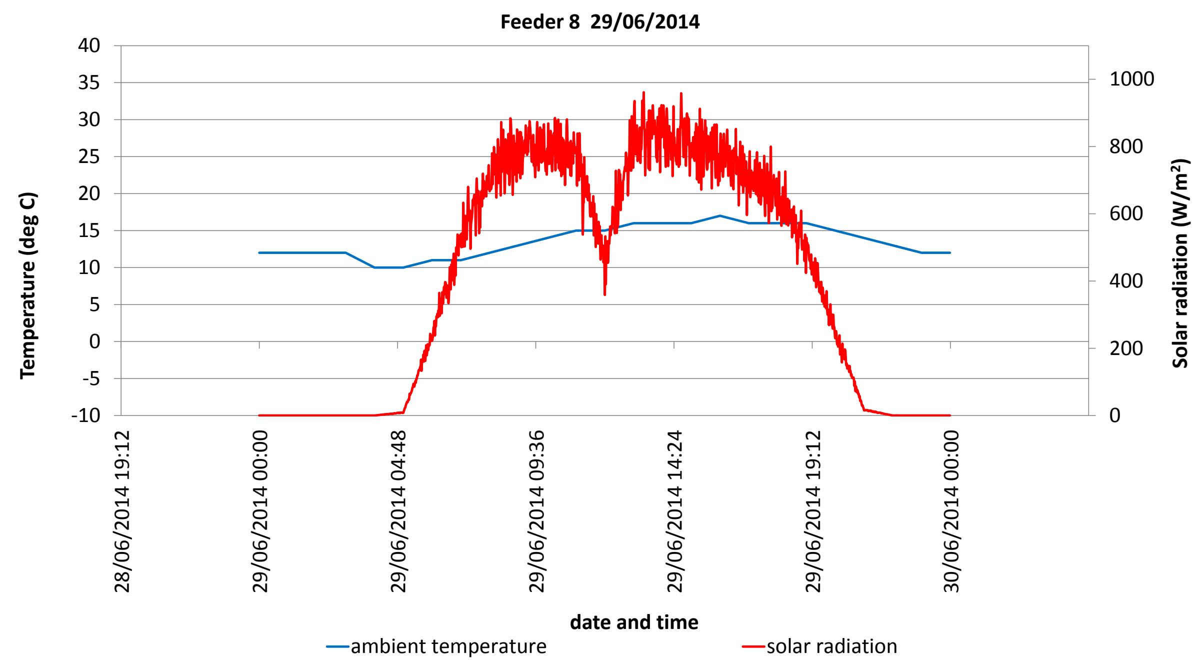


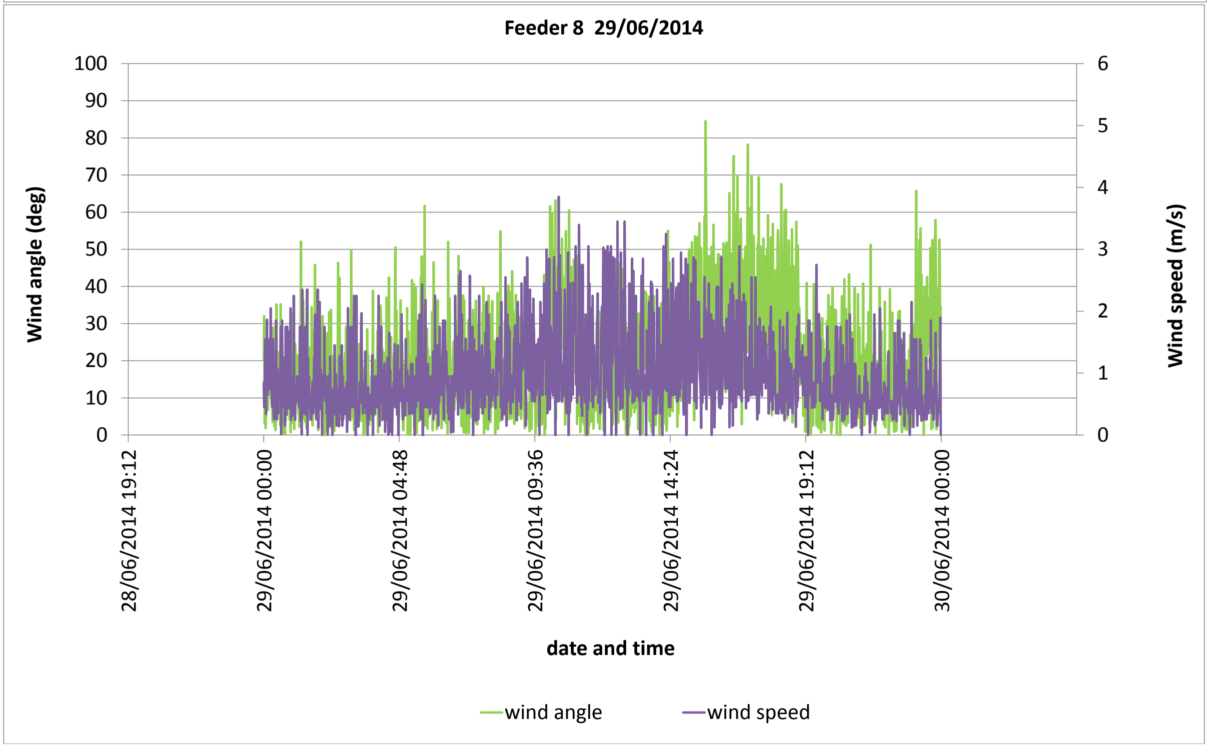
Day ahead predicted data for Spring Sunday 22/03/15



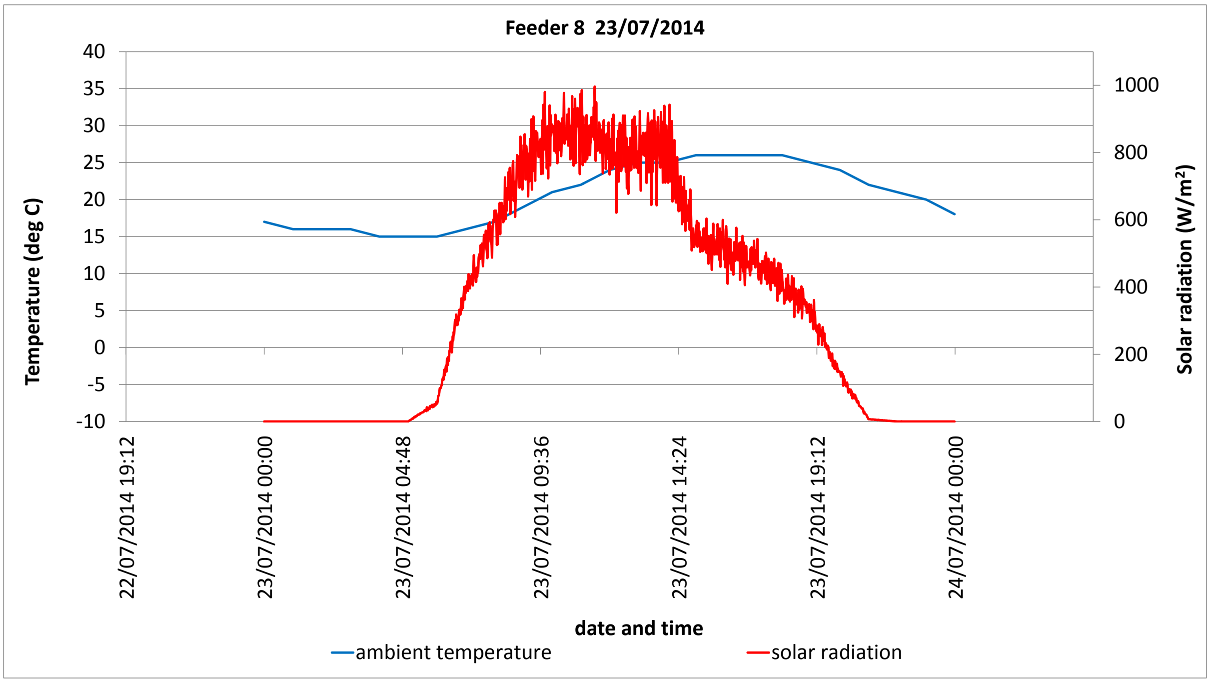


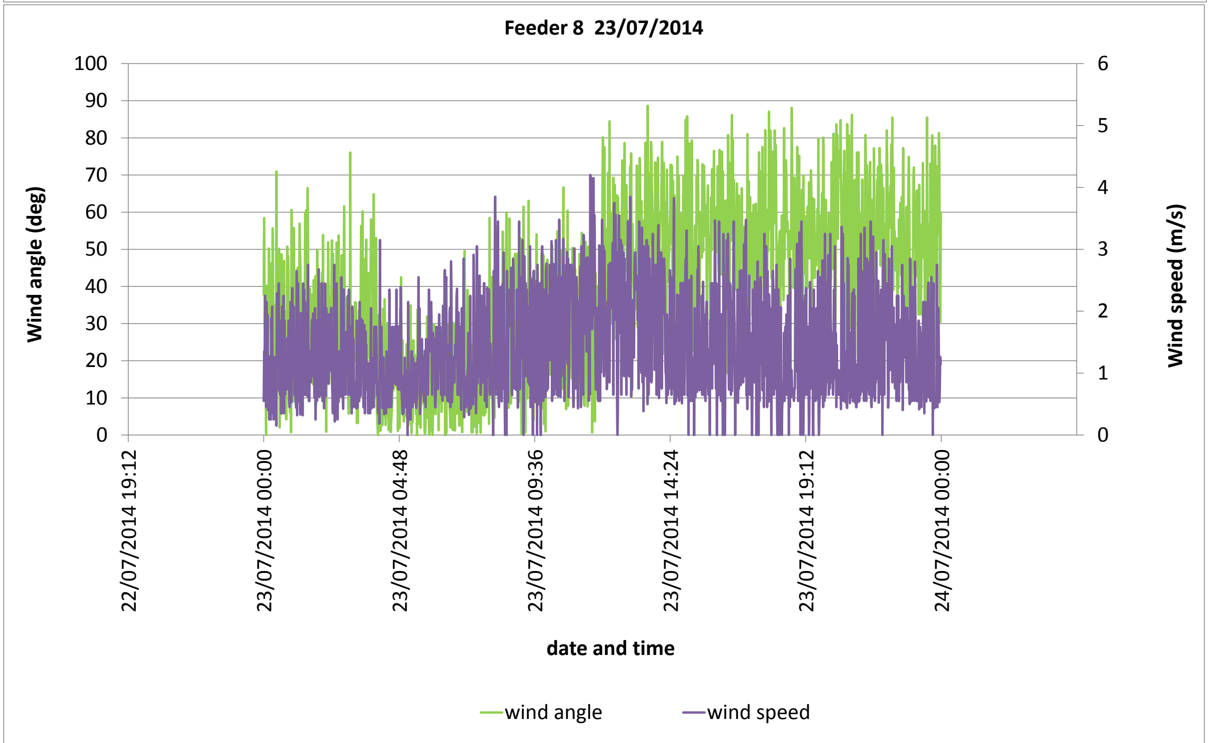
Day ahead predicted data for Summer Wednesday 25/06/14



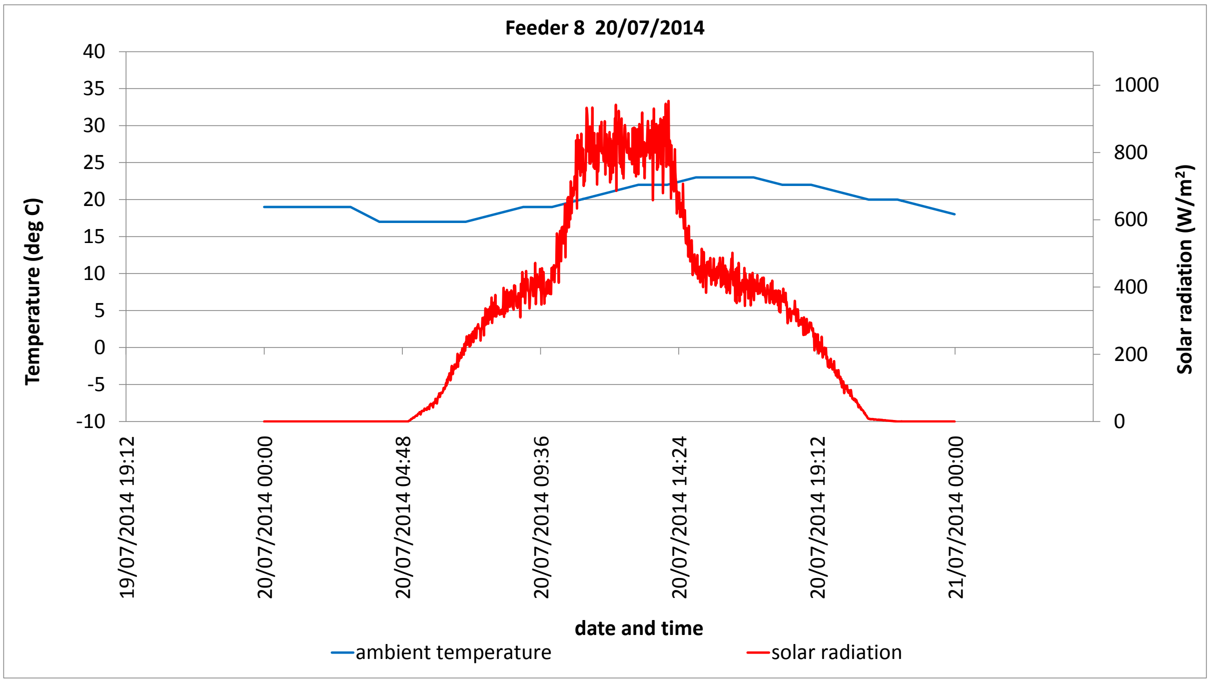


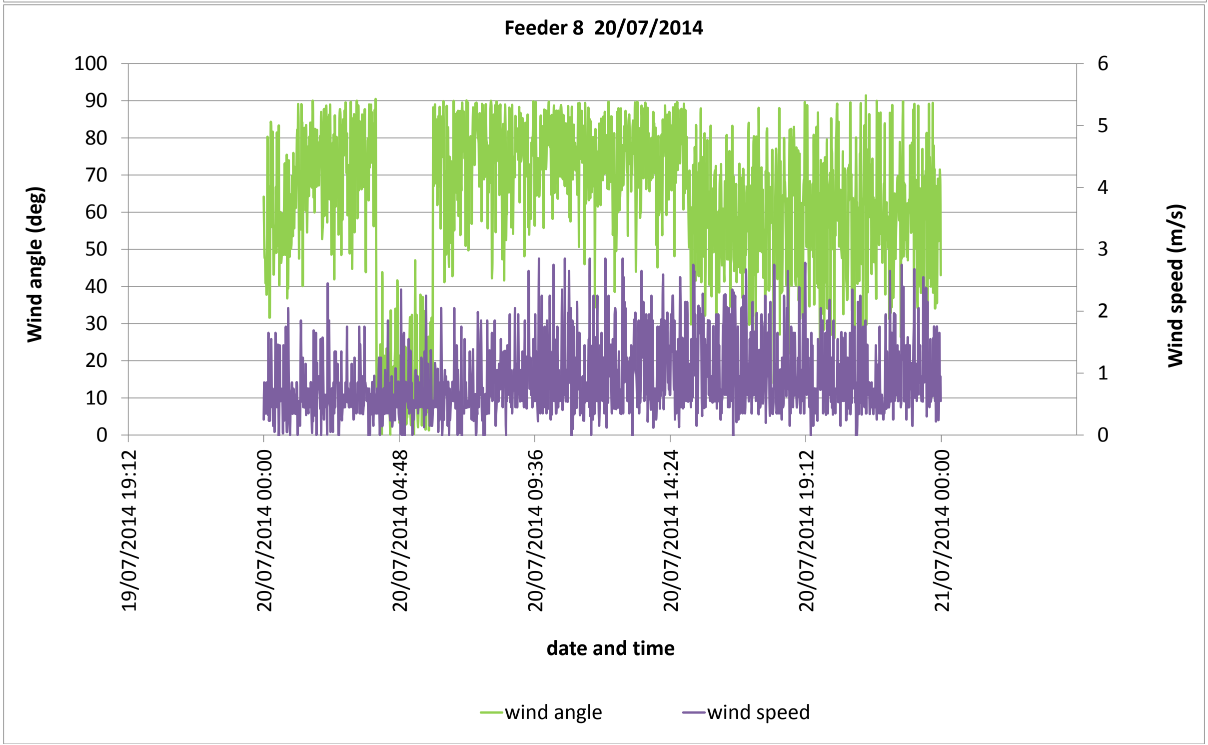
Day ahead predicted data for Summer Sunday 29/06/14



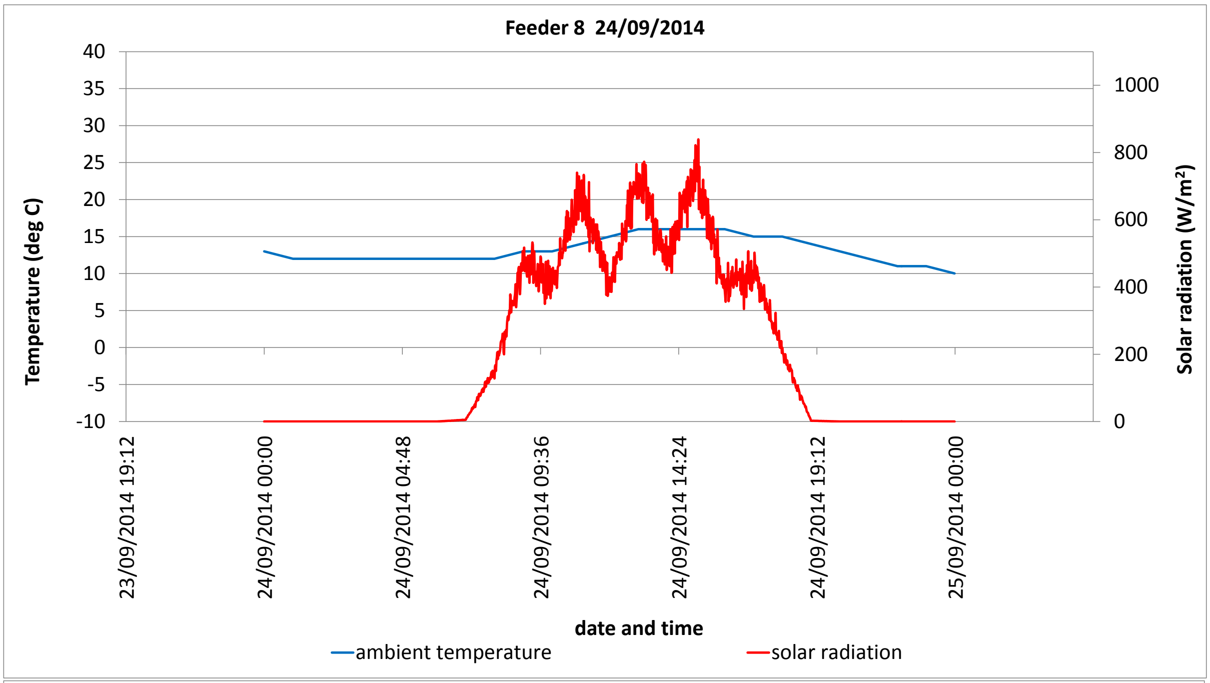


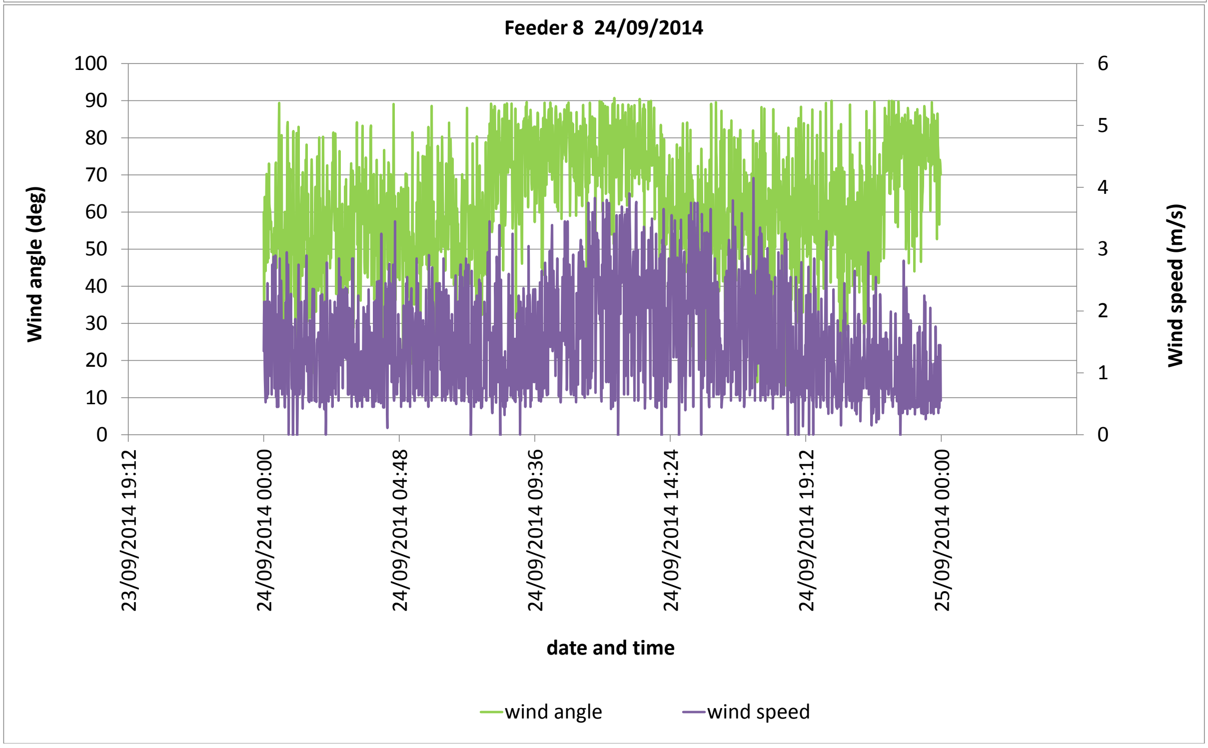
Day ahead predicted data for High Summer Wednesday 23/07/14



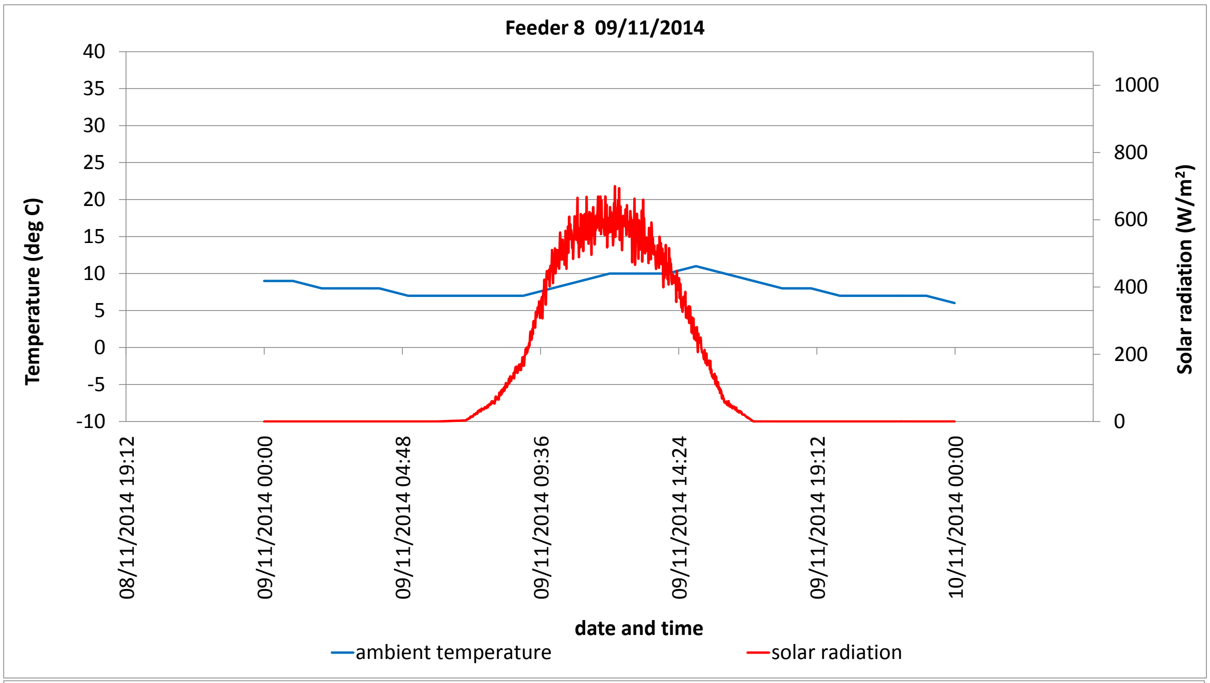


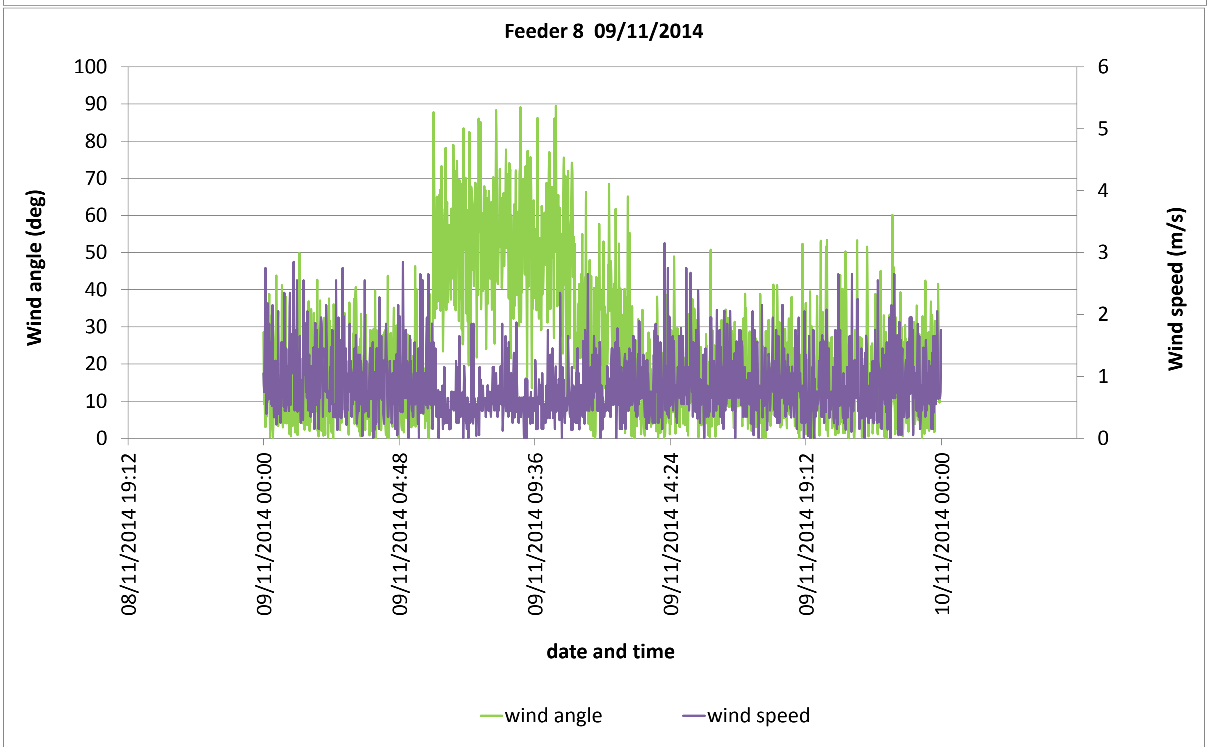
Day ahead predicted data for High Summer Sunday 20/07/14





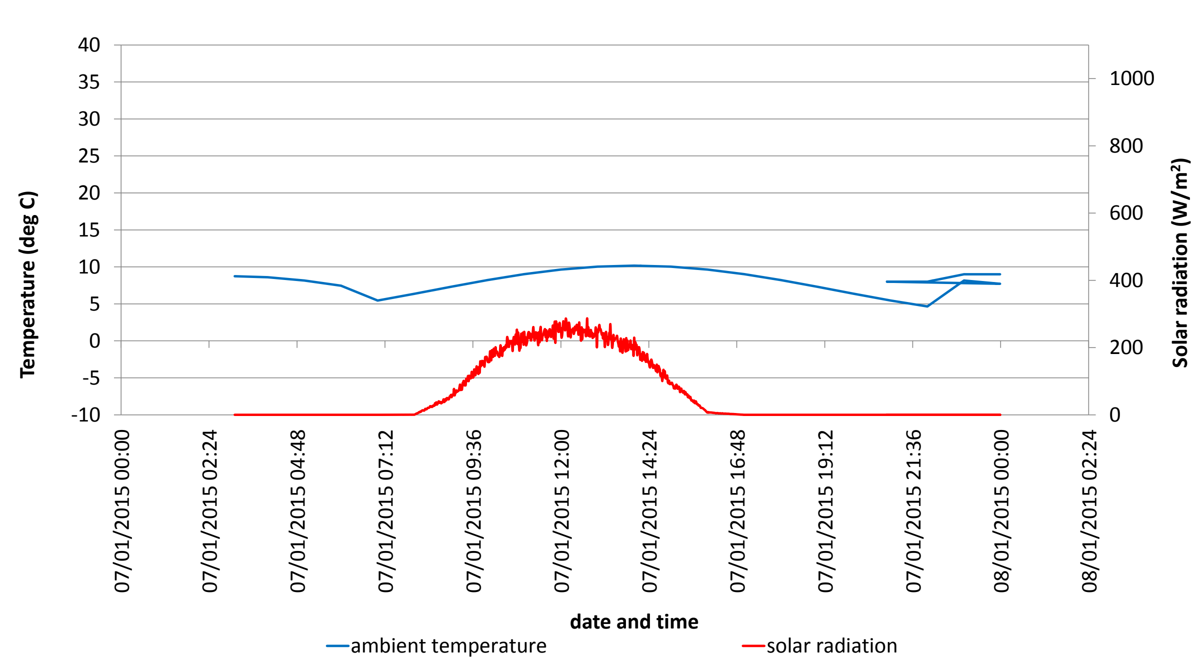
Day ahead predicted data for Autumn Wednesday 24/09/14

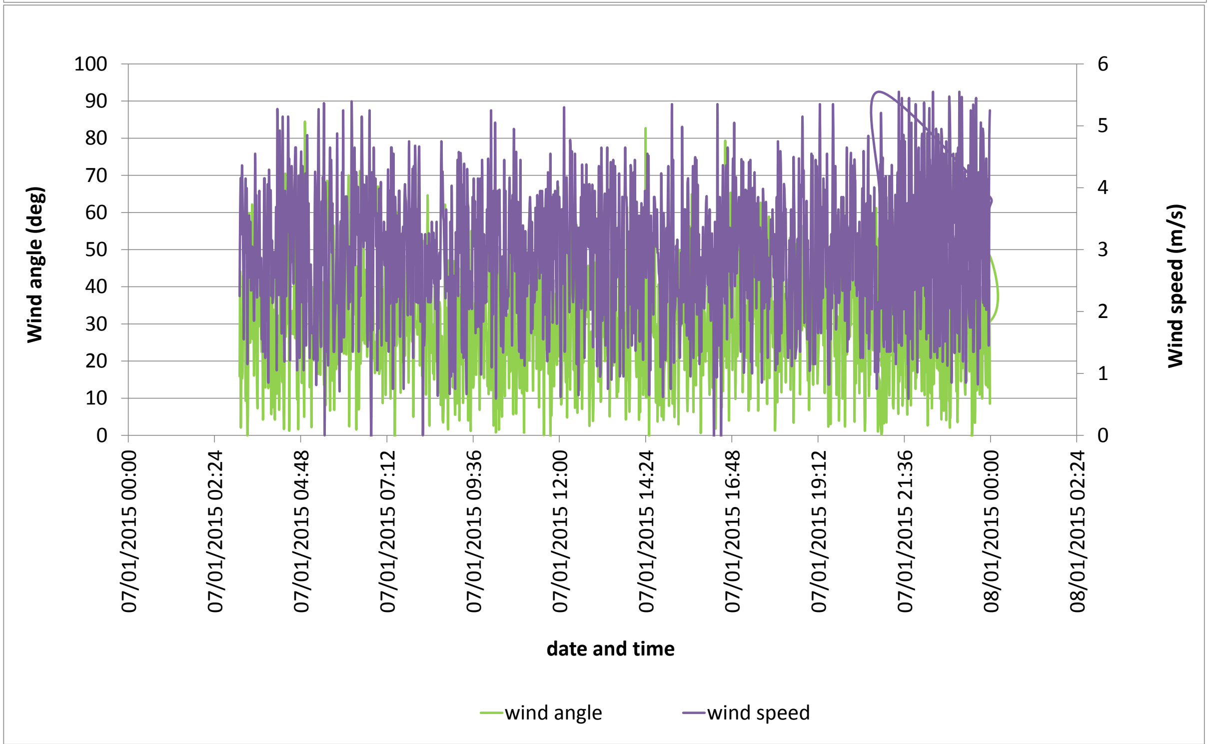




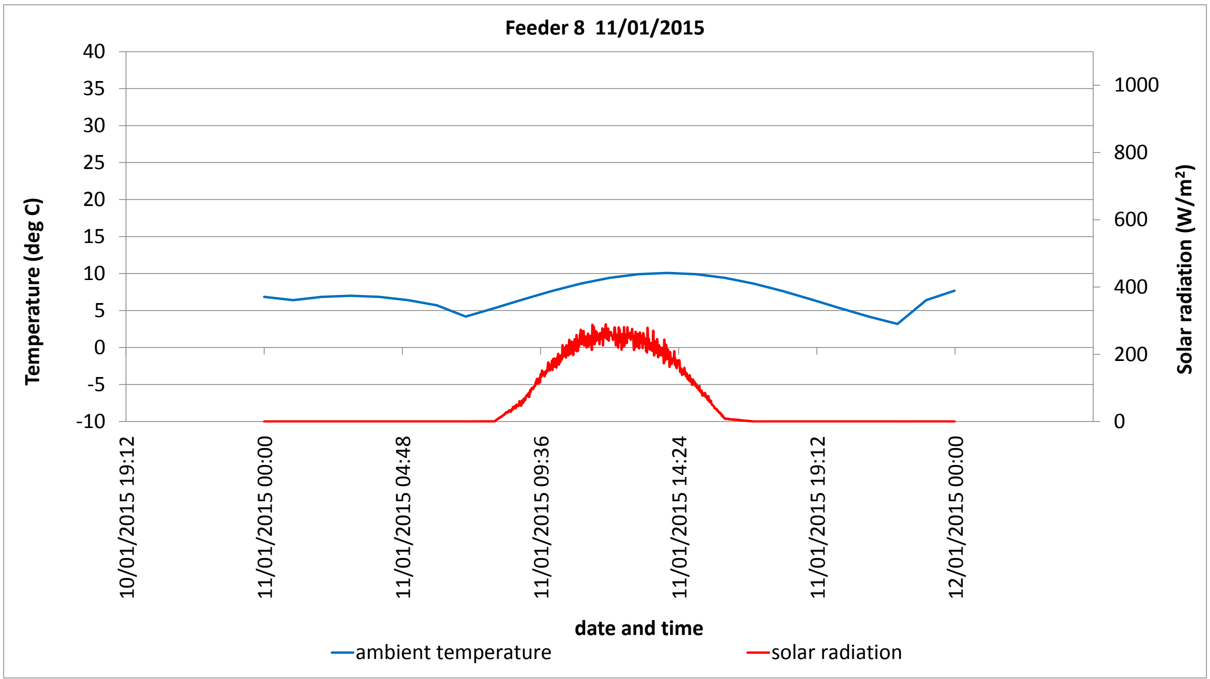
Day ahead predicted data for Autumn Sunday 09/11/14

H Week ahead predicted data

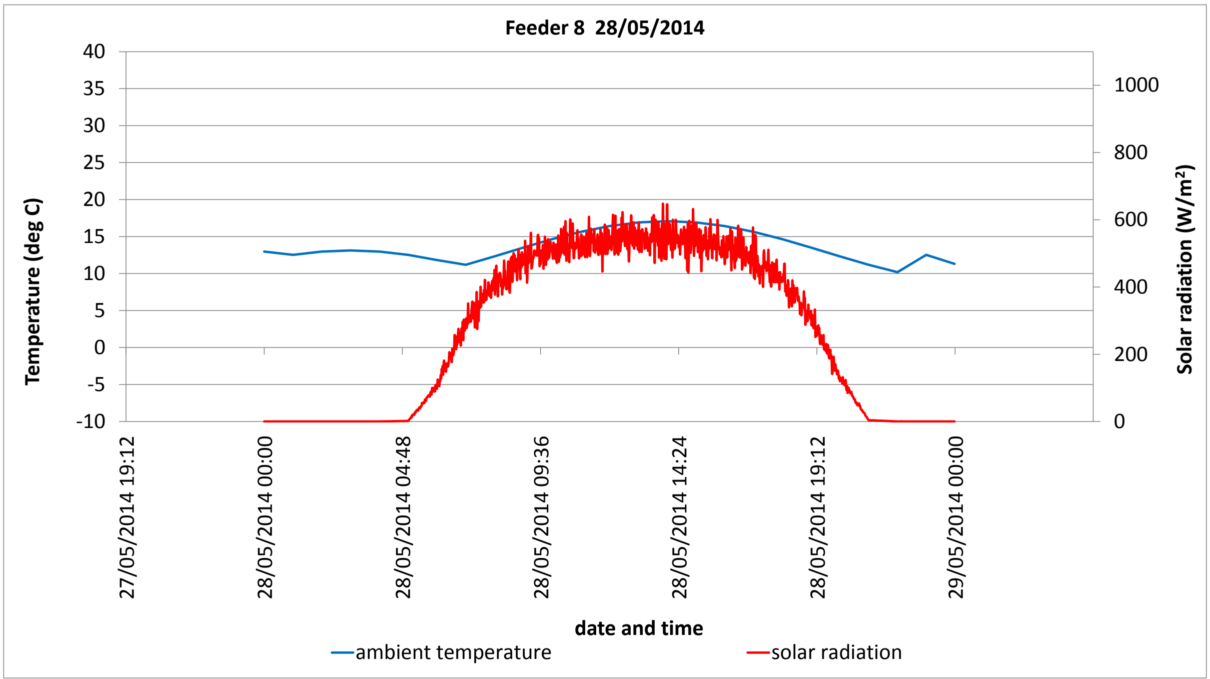


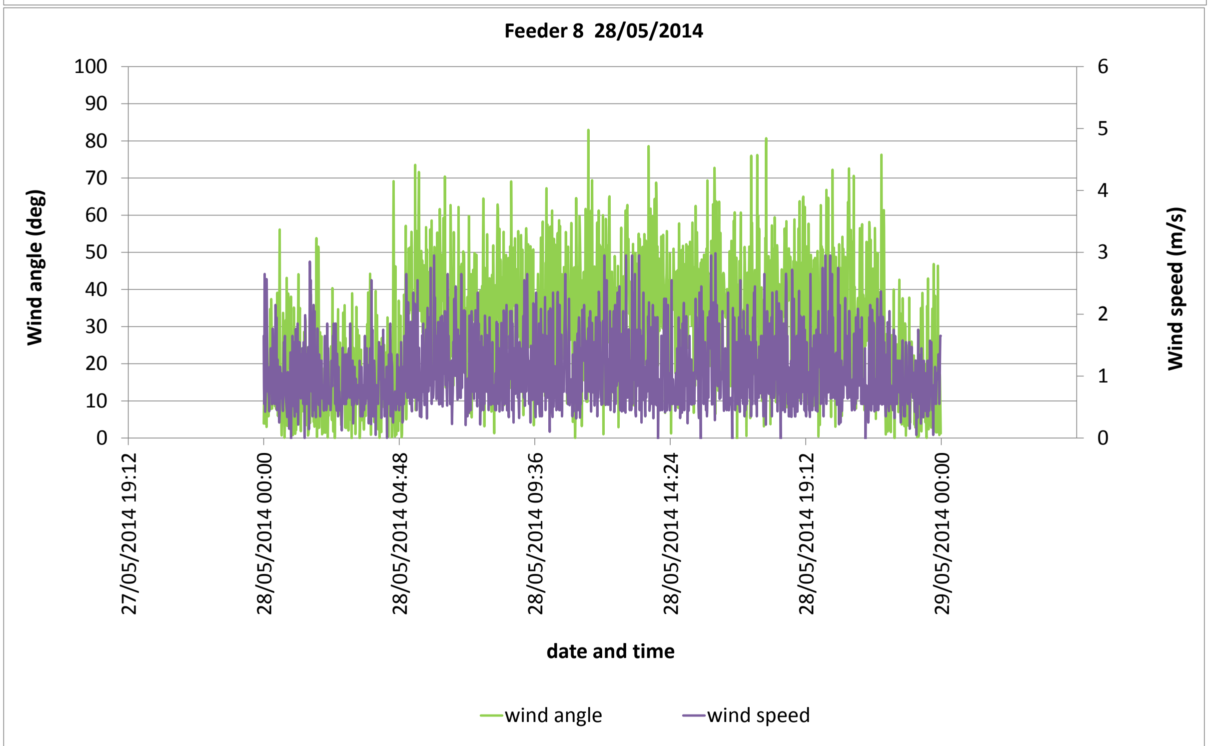


Week ahead predicted data for Winter Wednesday 07/01/15

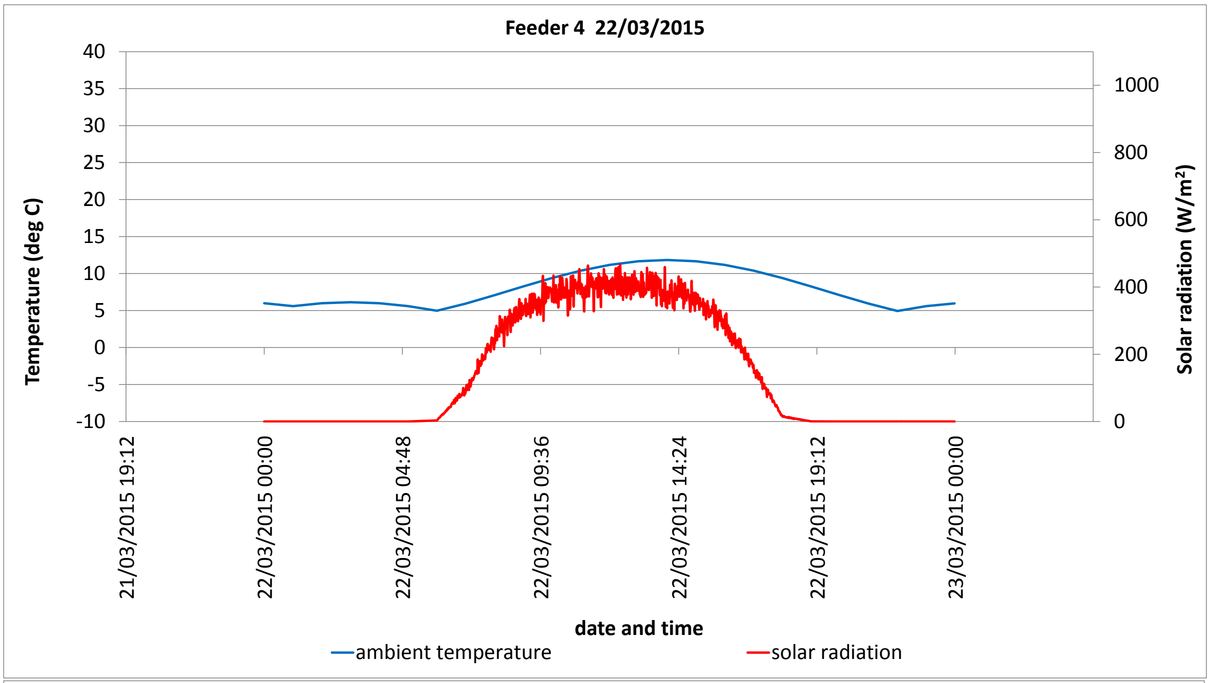


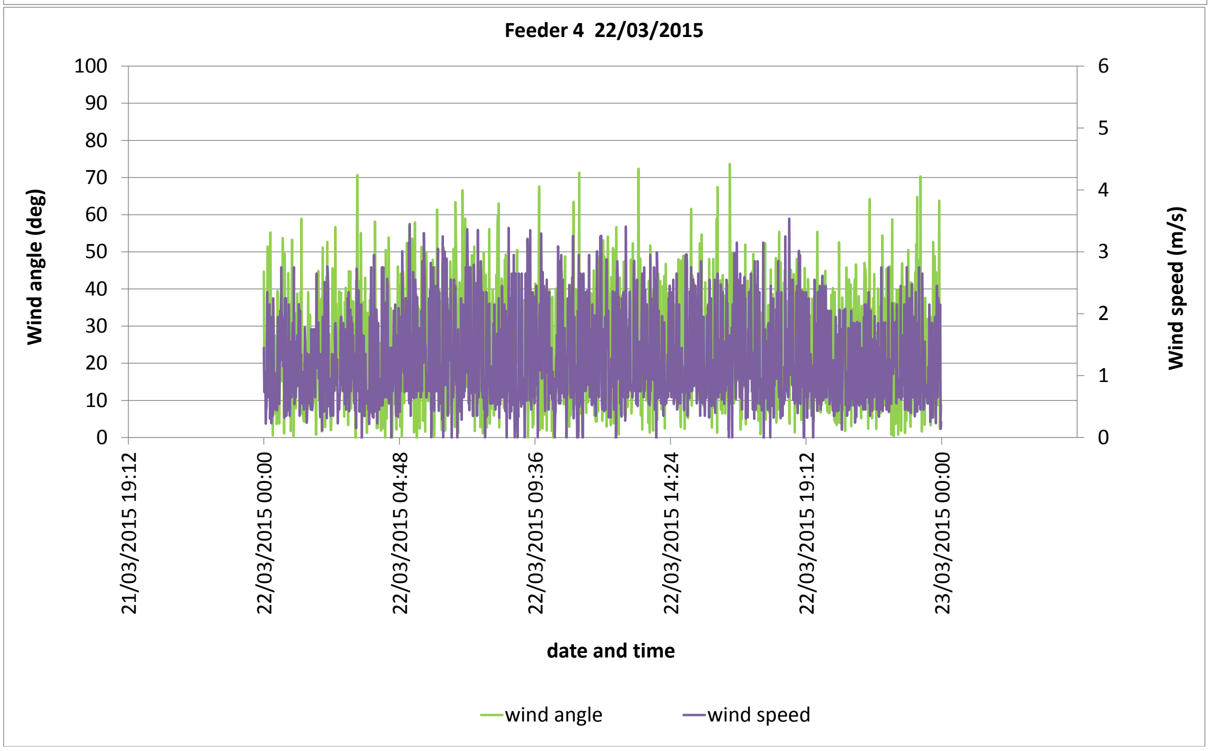
Week ahead predicted data for Winter Sunday 11/01/15



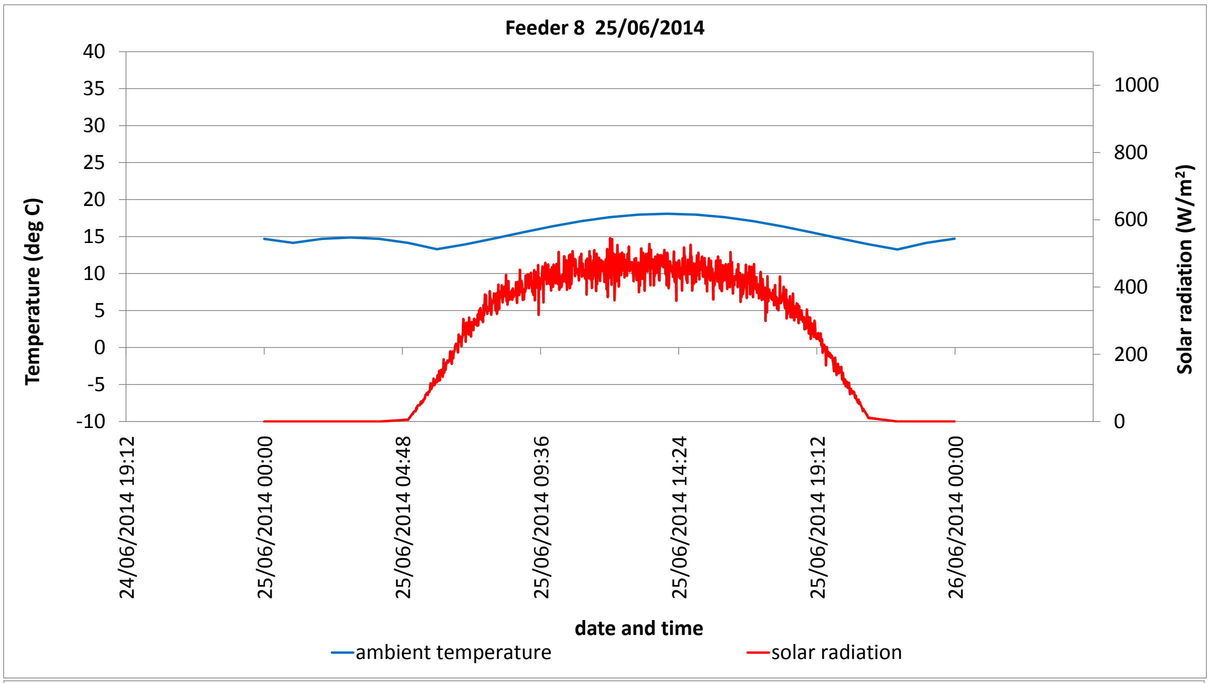


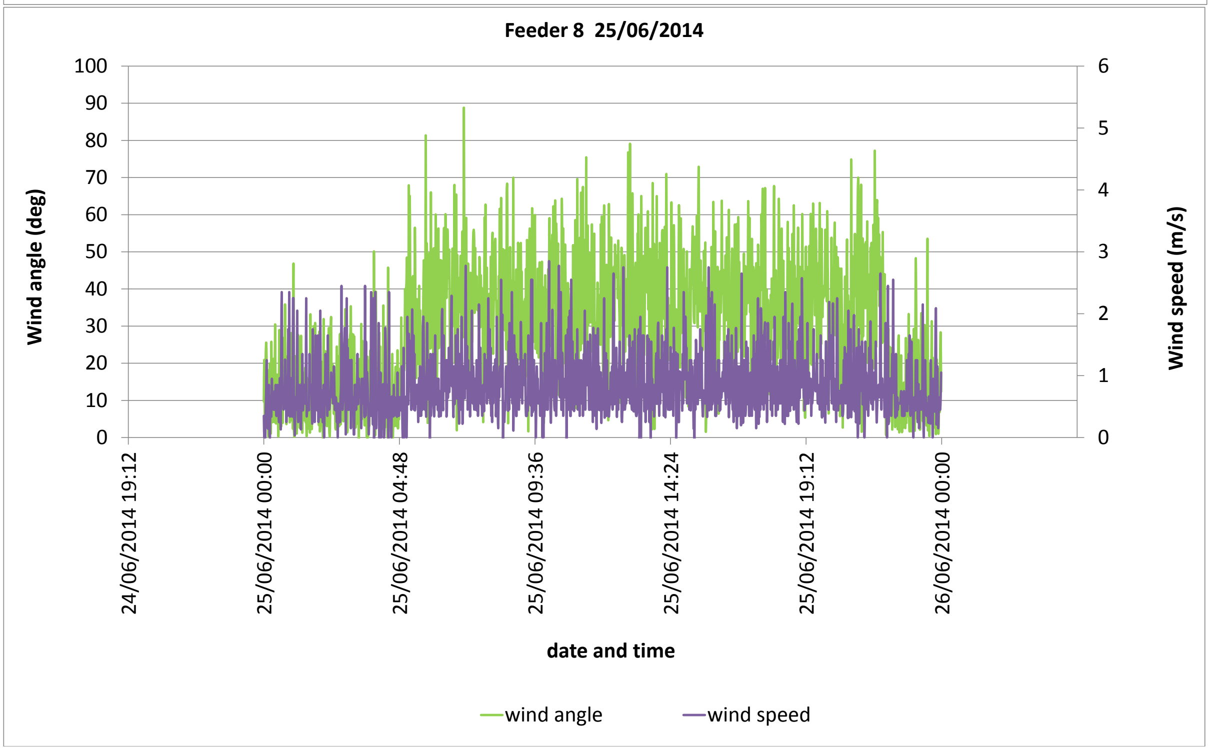
Week ahead predicted data for Spring Wednesday 28/05/14



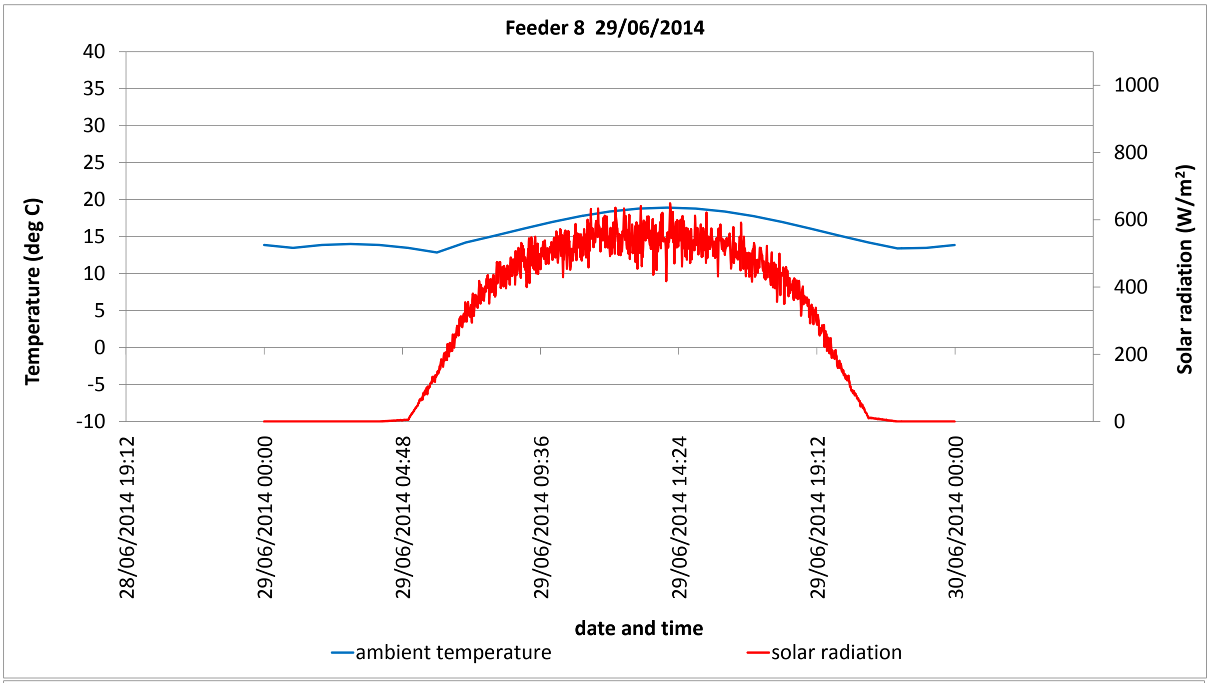


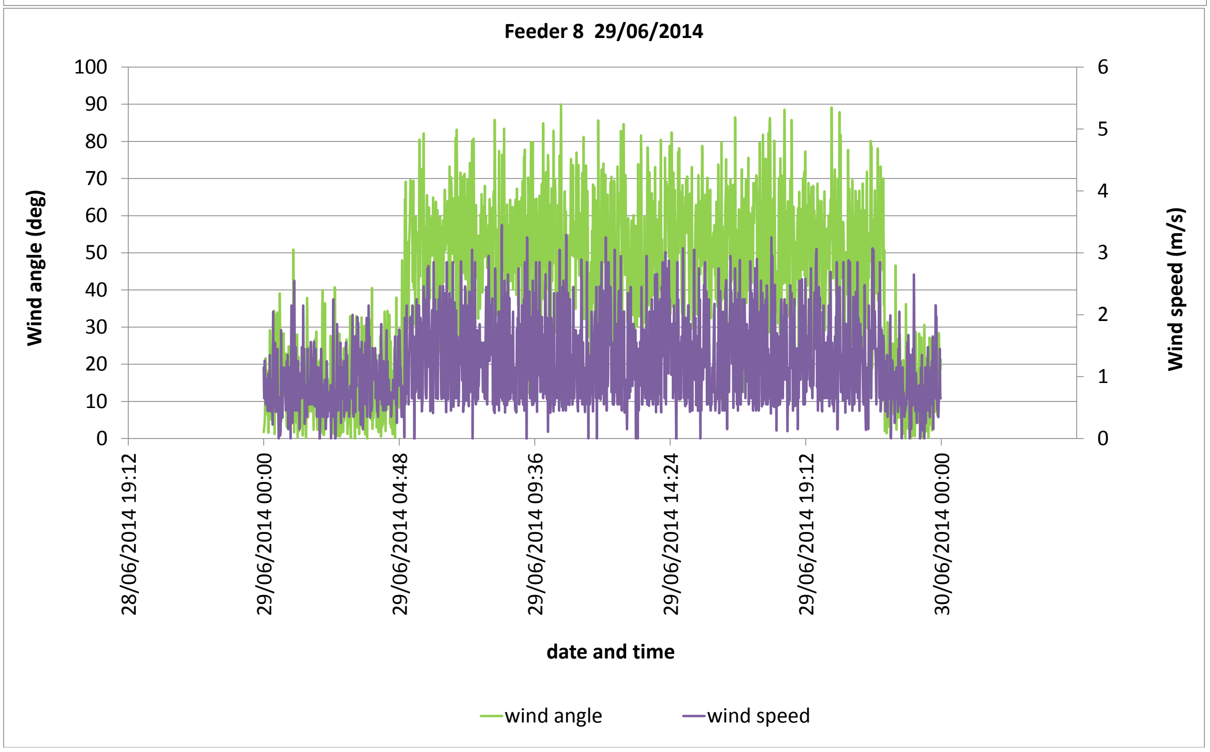
Day ahead predicted data for Spring Sunday 22/03/15



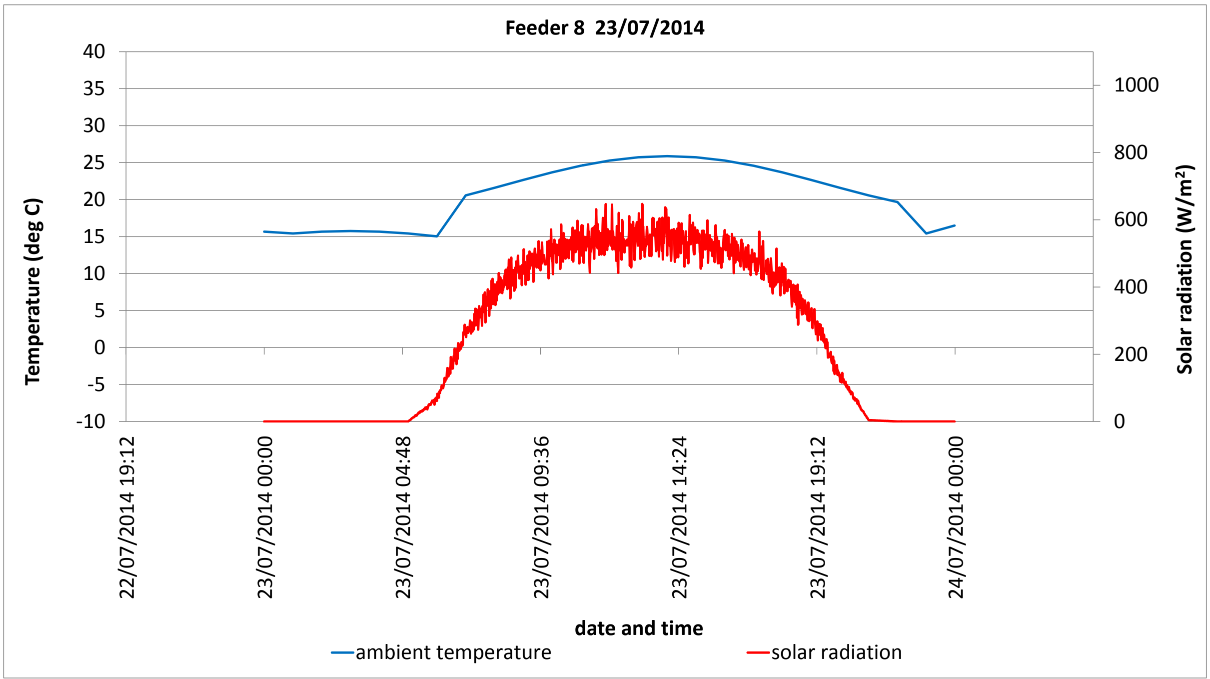


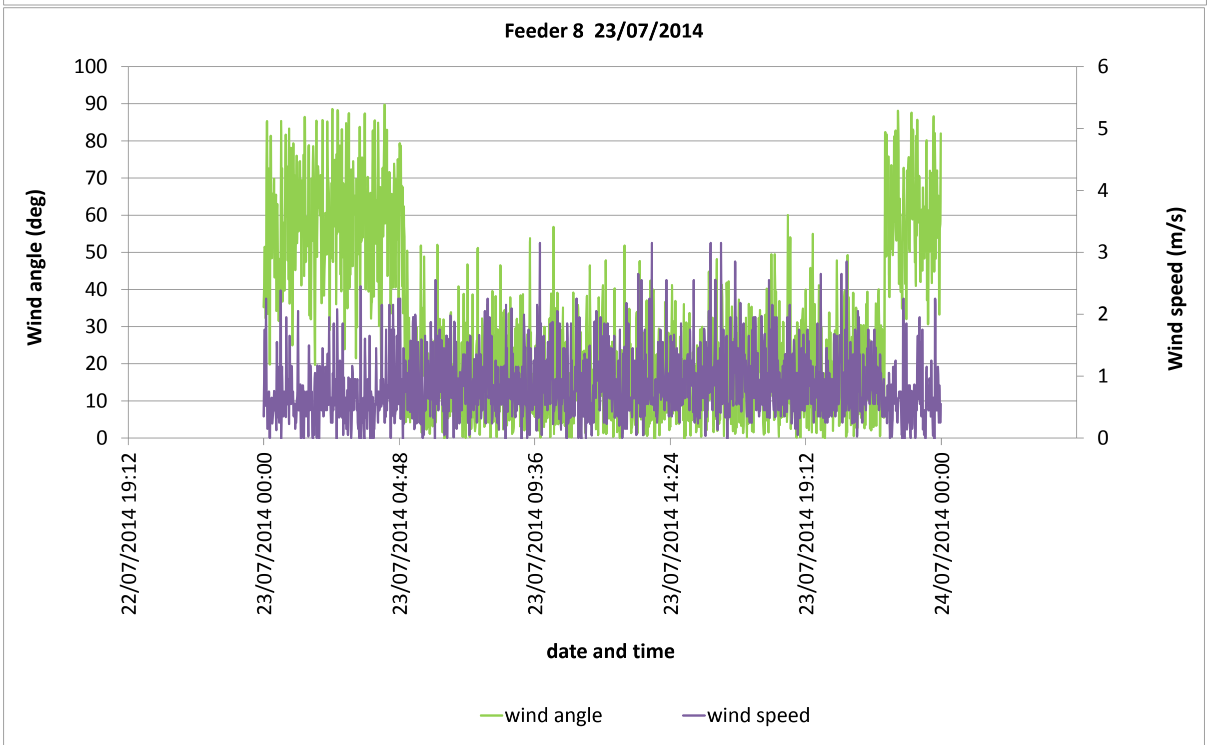
Week ahead predicted data for Summer Wednesday 25/06/14



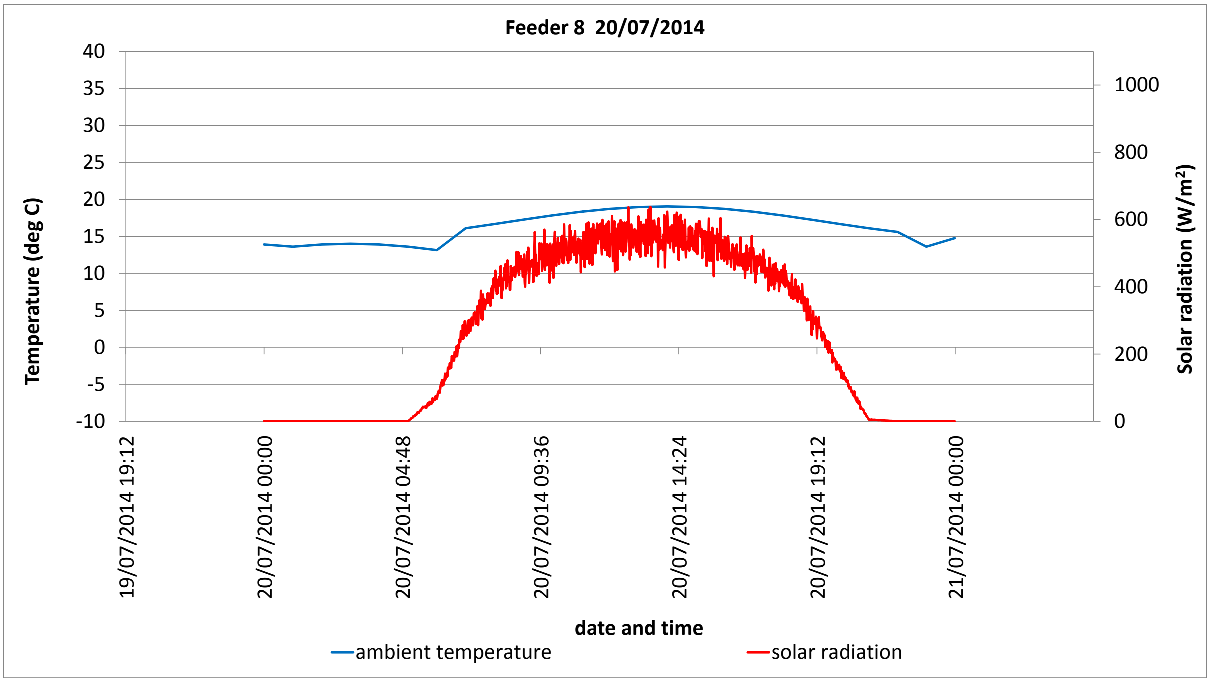


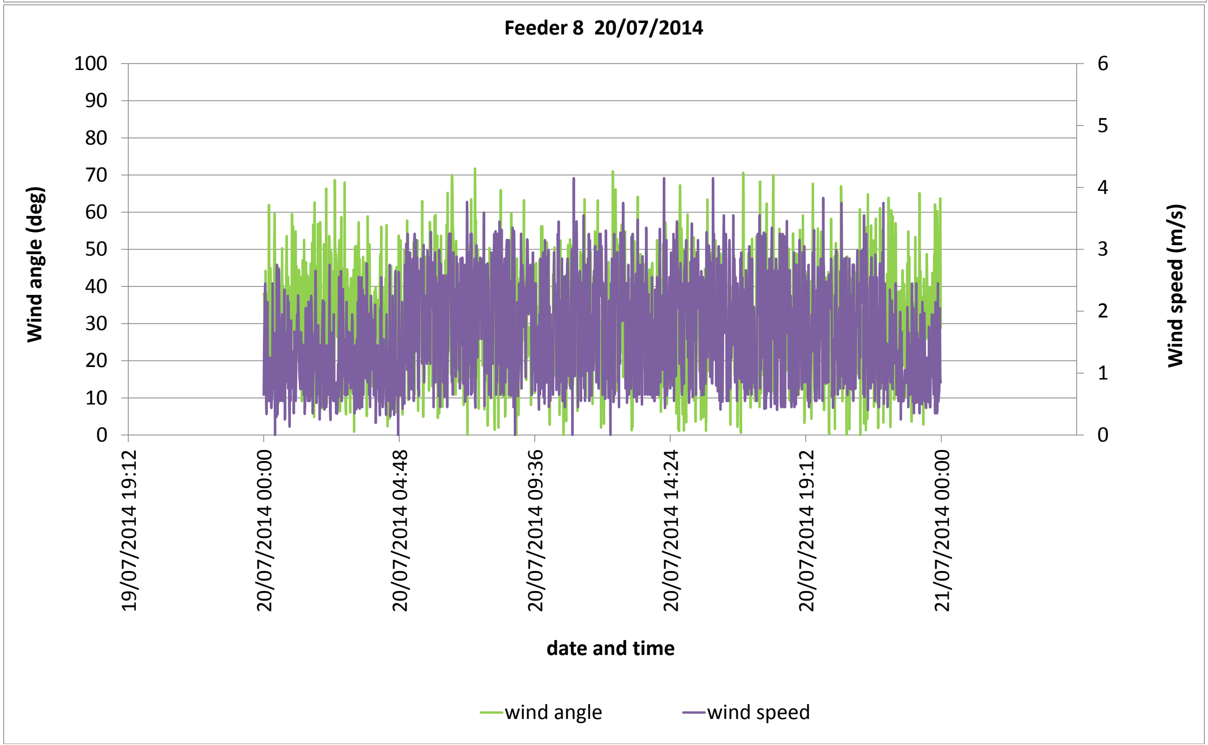
Week ahead predicted data for Summer Sunday 29/06/14



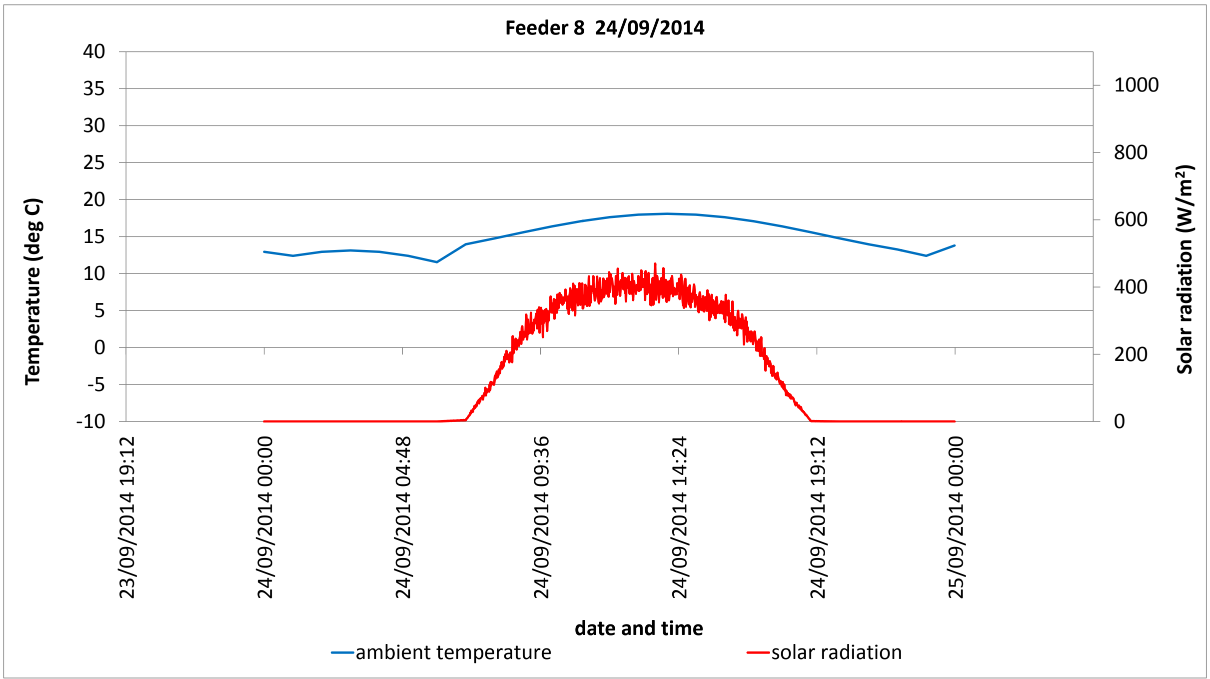


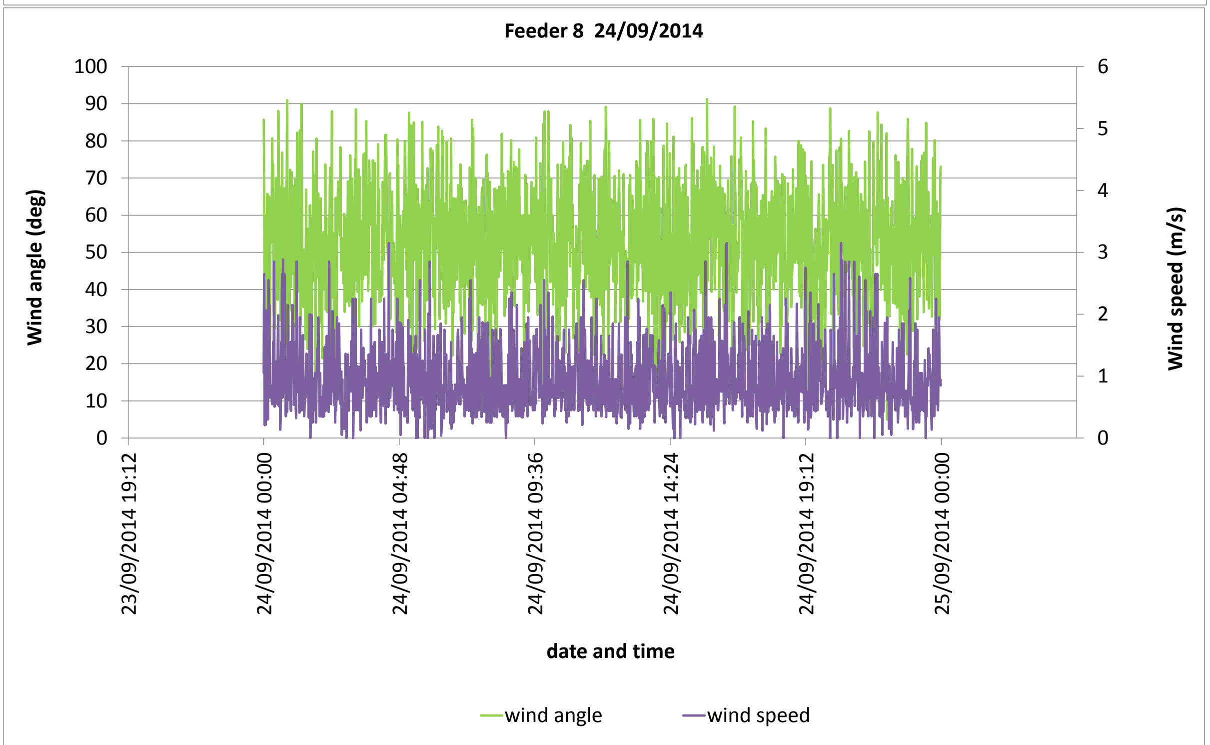
Week ahead predicted data for High Summer Wednesday 23/07/14



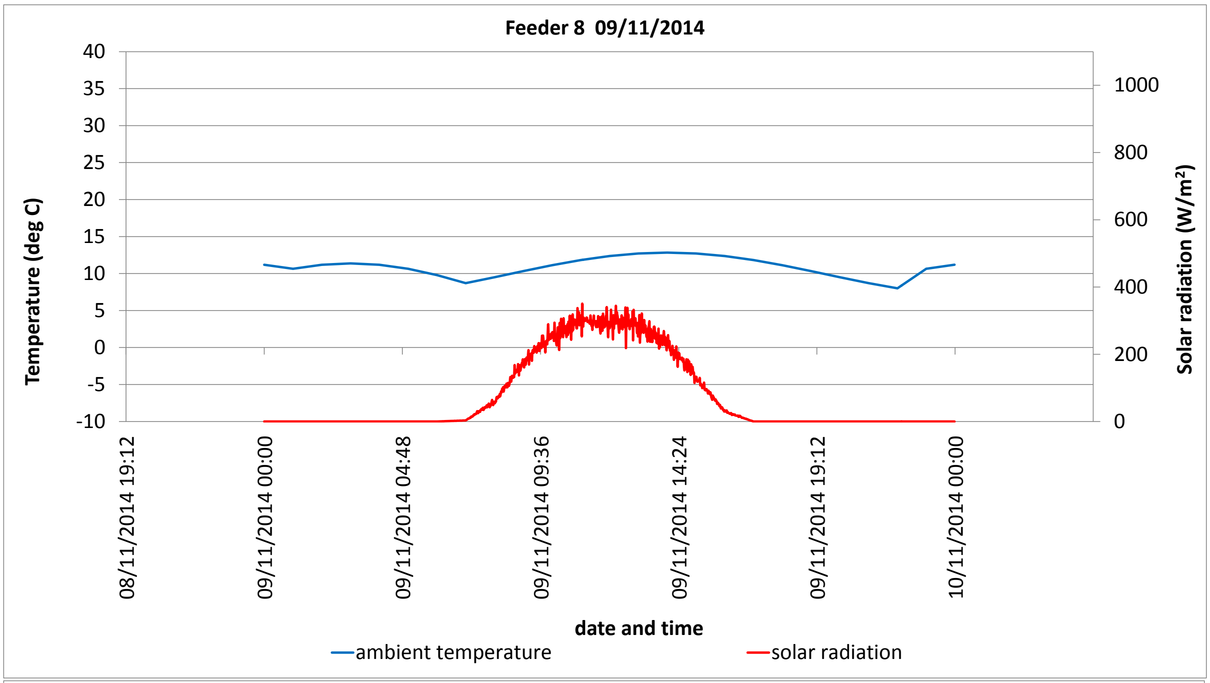


Week ahead predicted data for High Summer Sunday 20/07/14



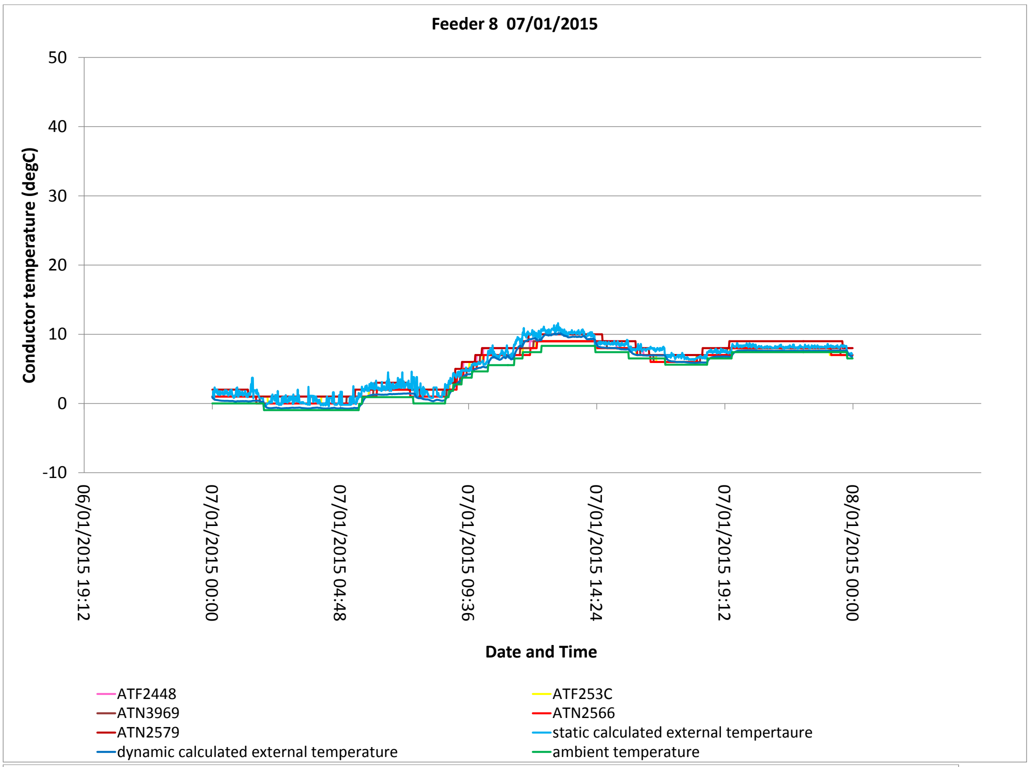


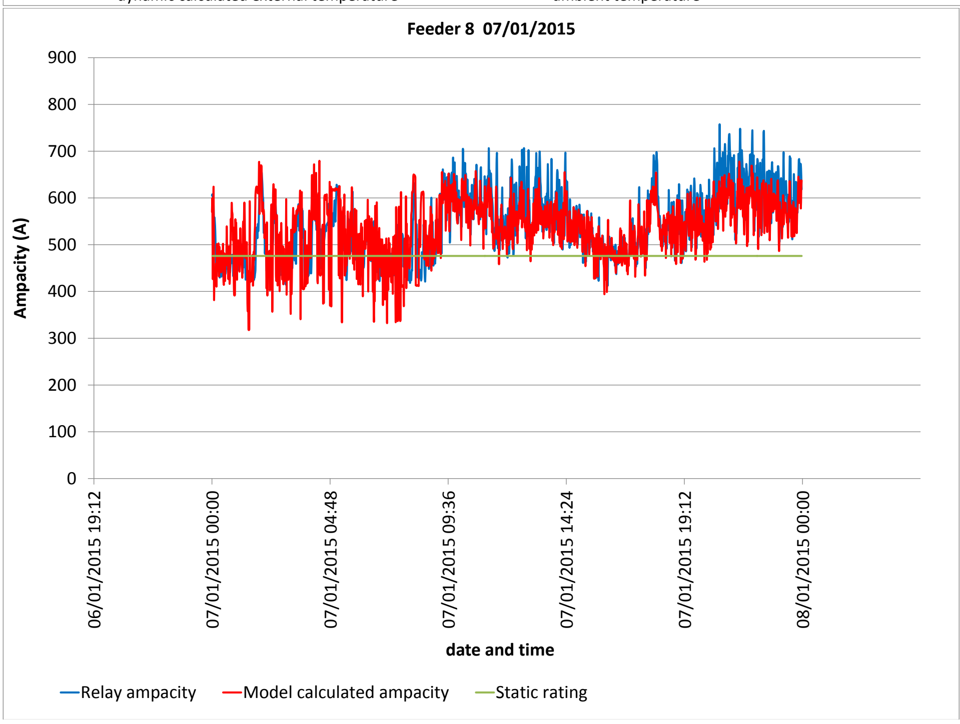
Week ahead predicted data for Autumn Wednesday 24/09/14



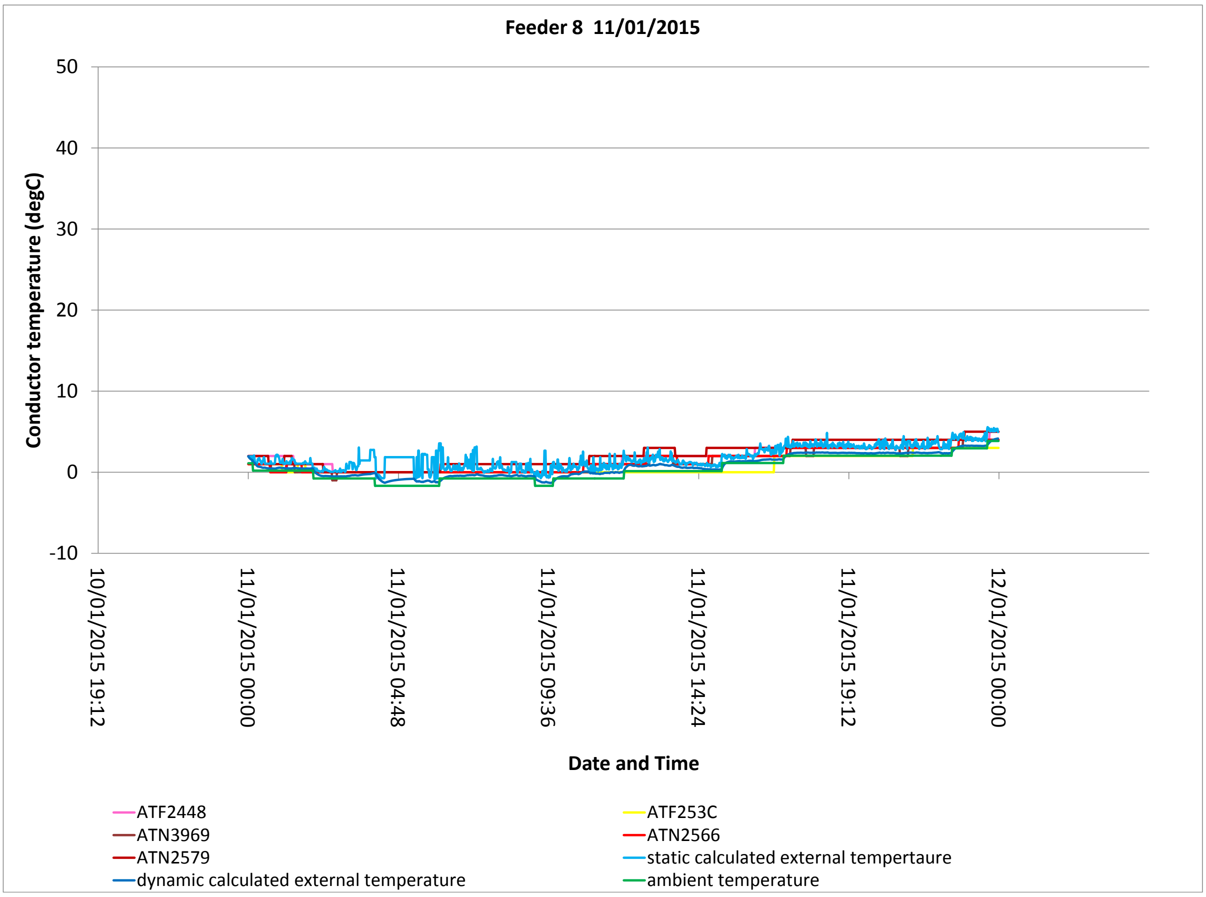
Week ahead predicted data for Autumn Sunday 09/11/14

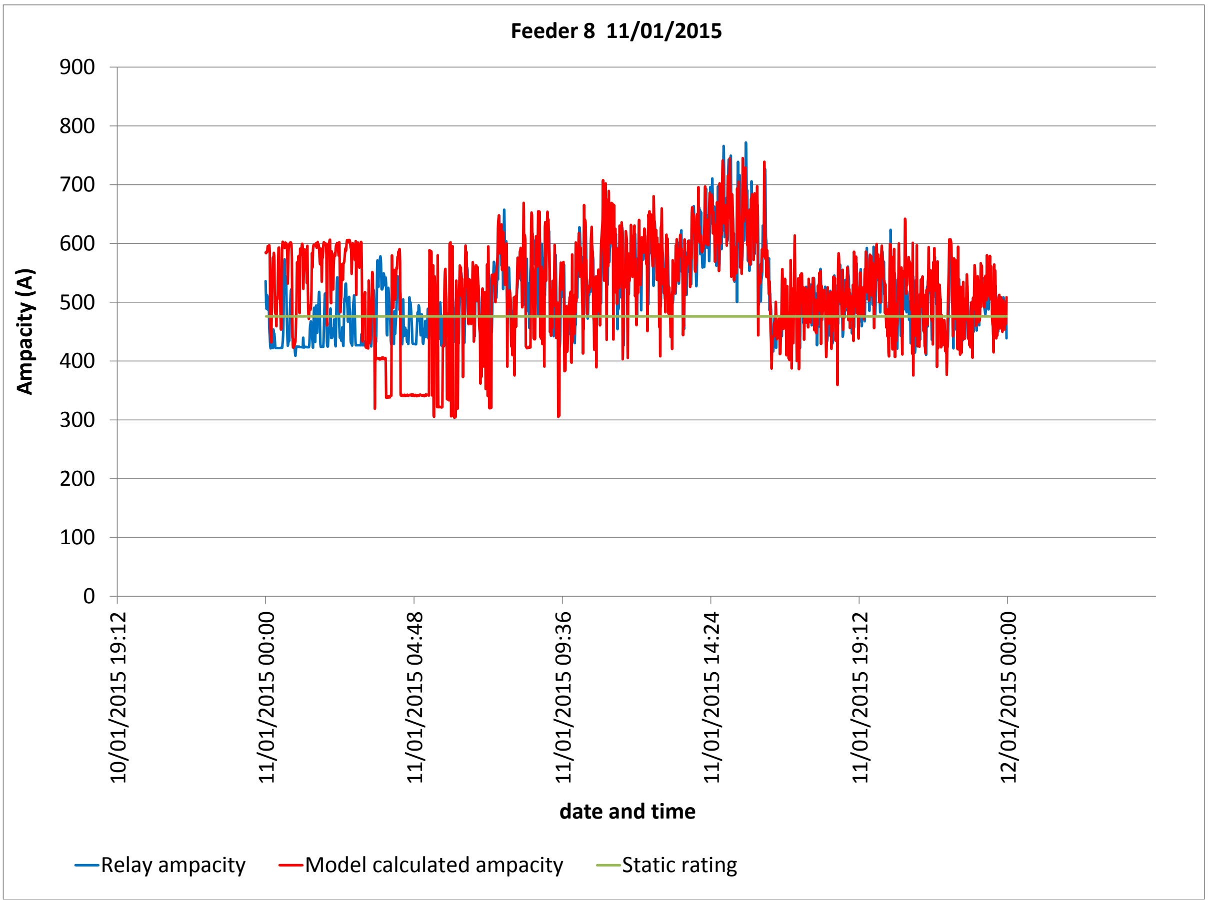
I Measured external temperature vs modelled temperature and reported relay rating vs modelled rating across the seasons.



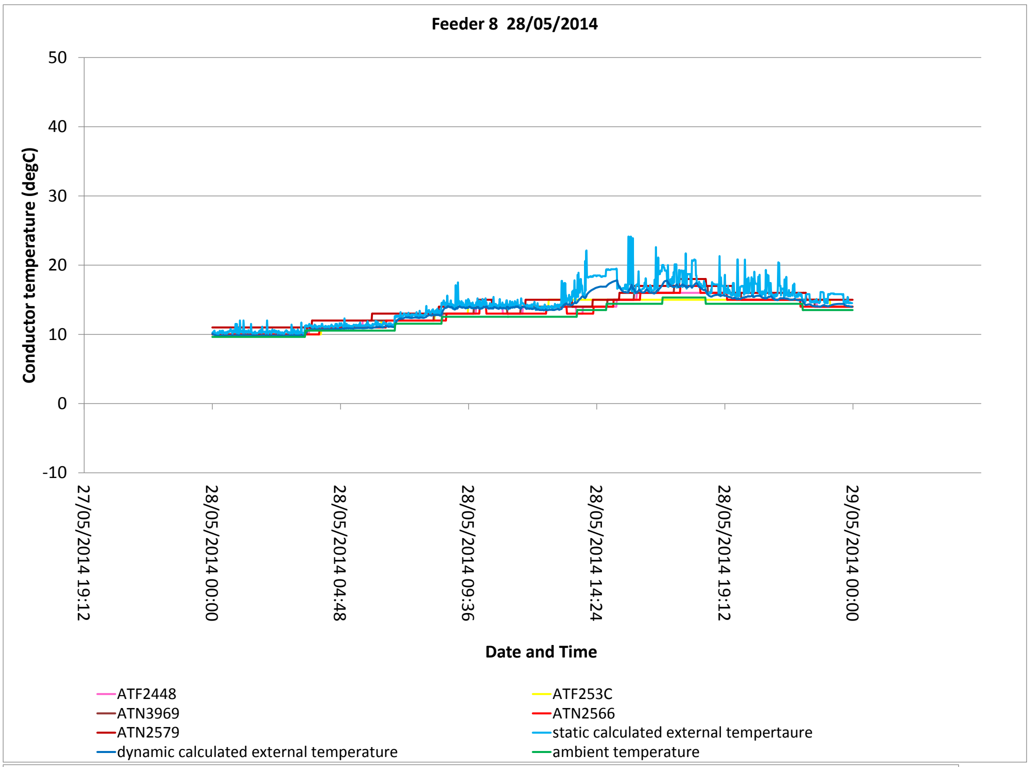


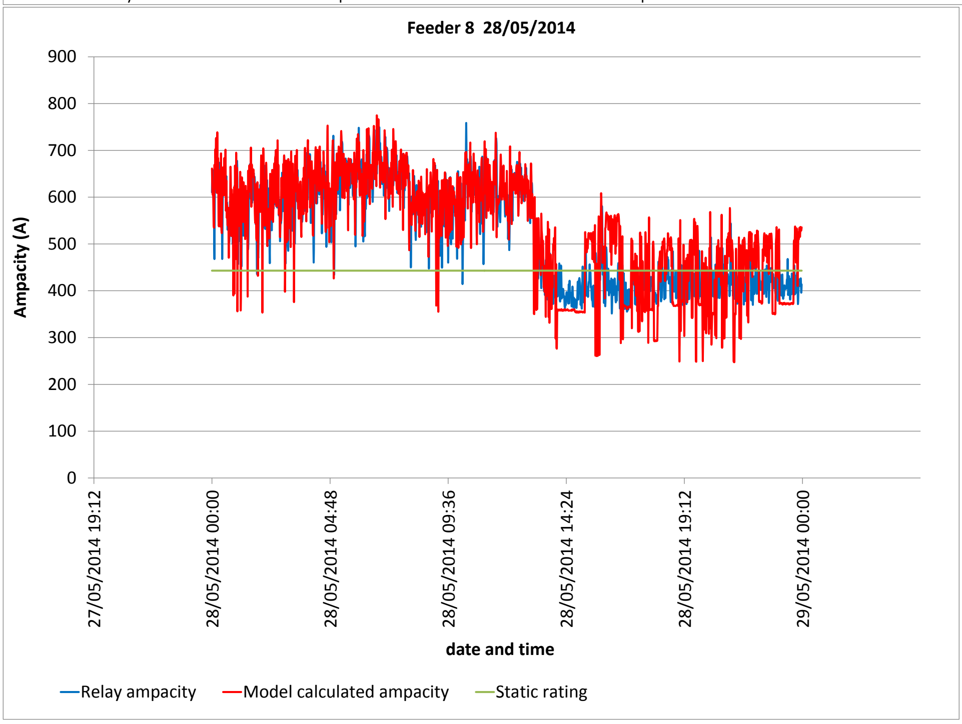
Feeder 8 : Winter Wednesday 07/01/15, model calculated temperature against toll grade reported temperature, model calculated ampacity against relay calculated ampacity


Feeder 8 11/01/2015
Conductor temperature (degC)
50
40
30
20
10
0
-10
10/01/2015 19:12
11/01/2015 00:00
11/01/2015 04:48
11/01/2015 09:36
11/01/2015 14:24
11/01/2015 19:12
12/01/2015 00:00
Date and Time
ATF2448
ATF253C
ATN3969
ATN2566
ATN2579
static calculated external tempertaure
dynamic calculated external temperature
ambient temperature

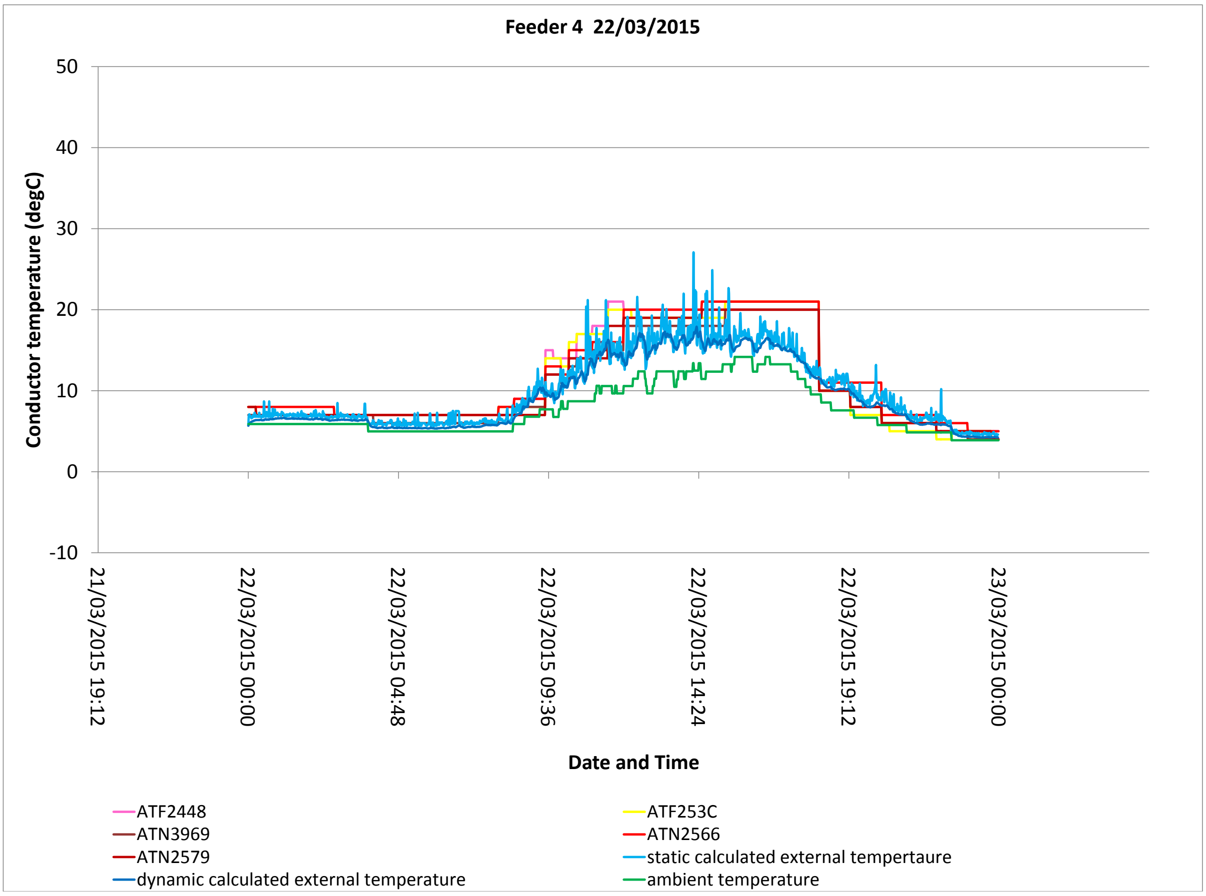


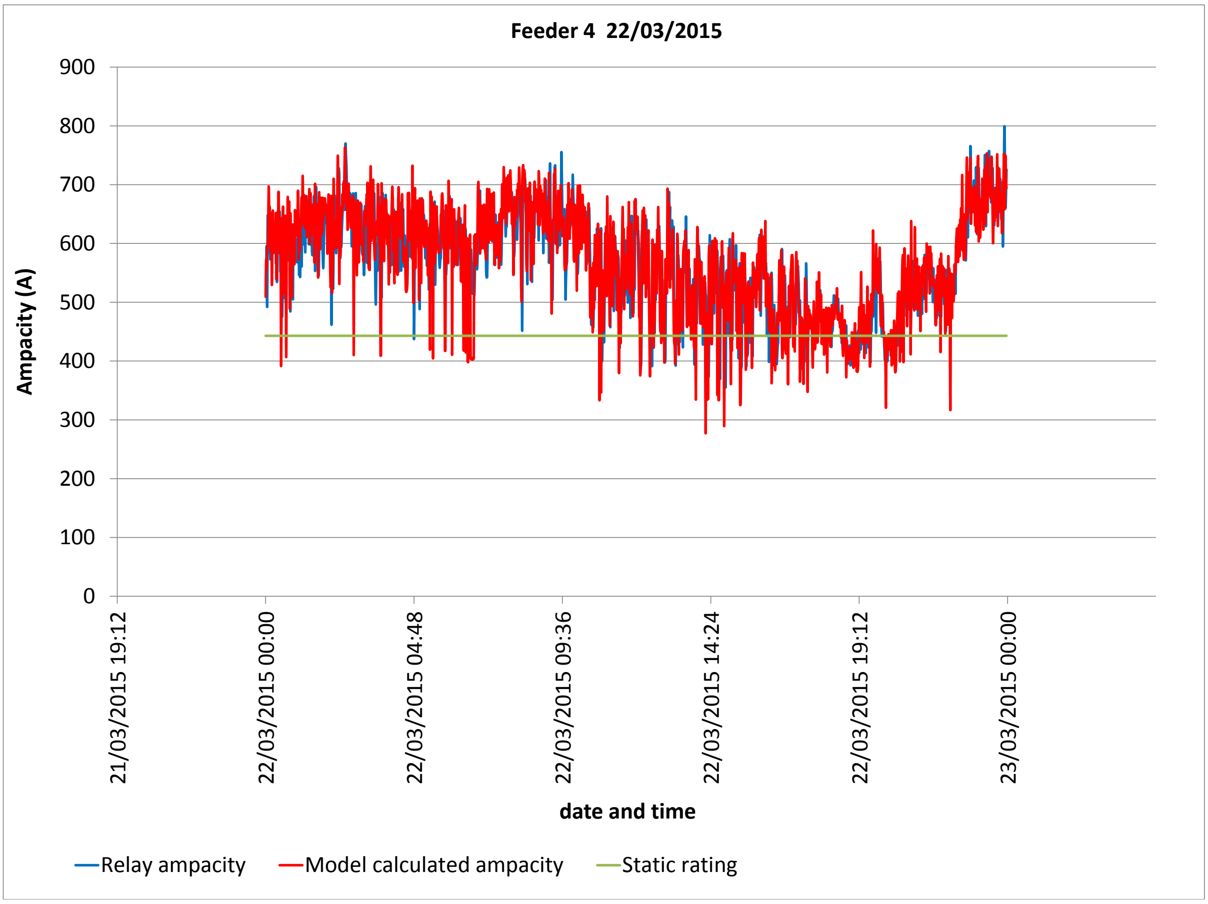
Feeder 8 : Winter Sunday 11/01/15, model calculated temperature against toll grade reported temperature, model calculated ampacity against relay calculated ampacity



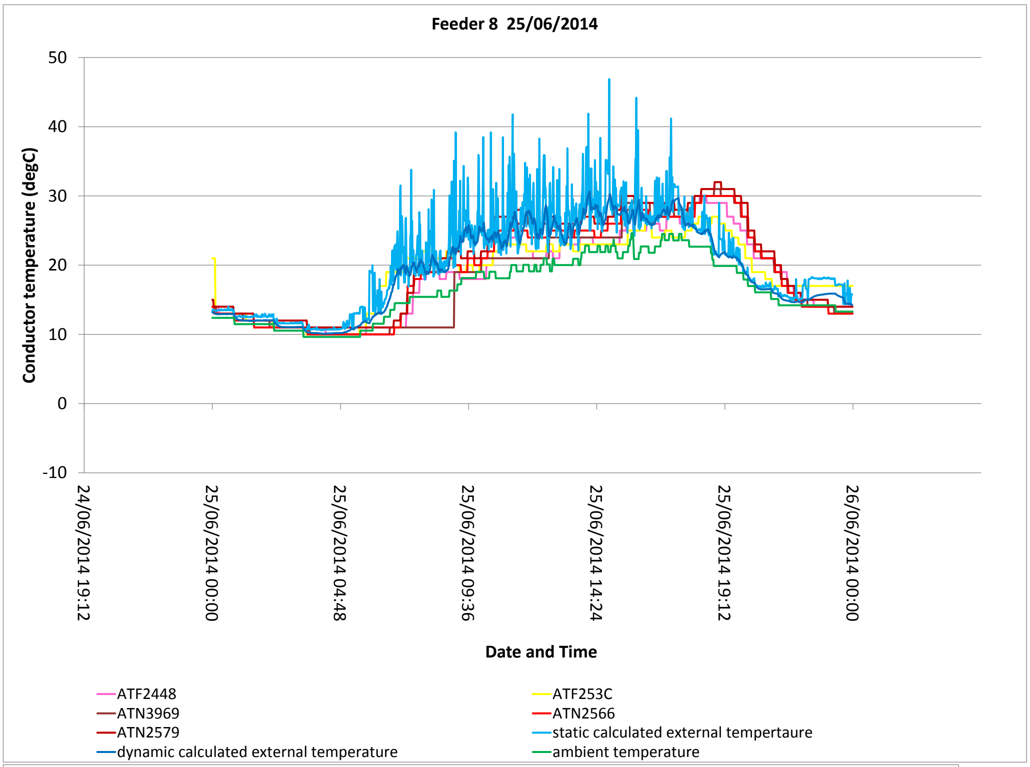


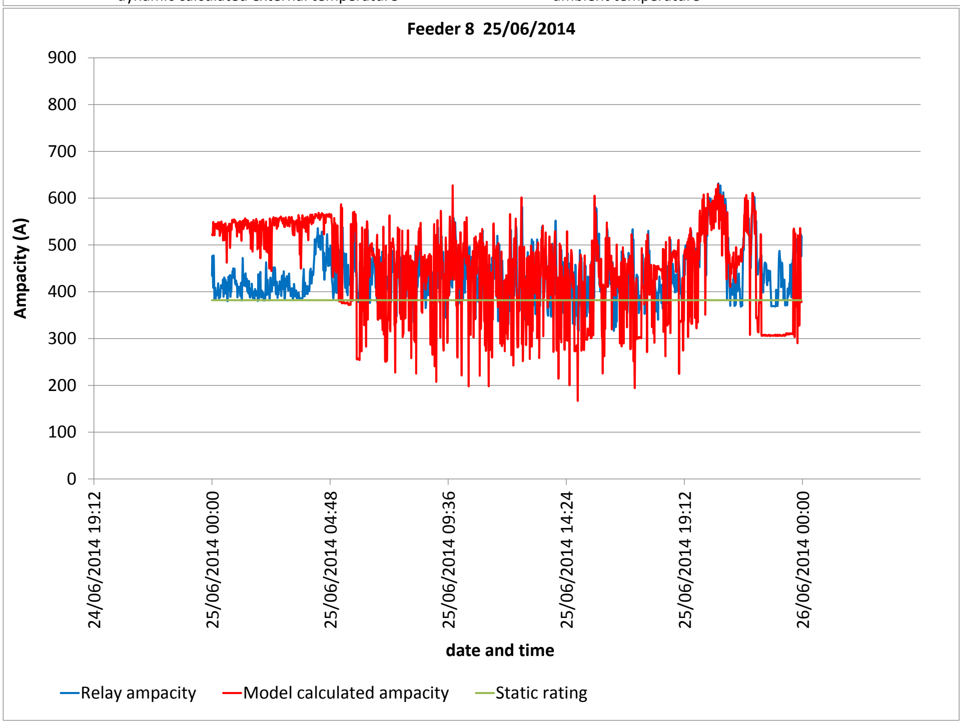
Feeder 8 :Spring Wednesday 28/05/15, model calculated temperature against toll grade reported temperature, model calculated ampacity against relay calculated ampacity


Feeder 4 22/03/2015
Conductor temperature (degC)
50
40
30
20
10
0
-10
21/03/2015 19:12
22/03/2015 00:00
22/03/2015 04:48
22/03/2015 09:36
22/03/2015 14:24
22/03/2015 19:12
23/03/2015 00:00
Date and Time
ATF2448
ATF253C
ATN3969
ATN2566
ATN2579
static calculated external tempertaure
dynamic calculated external temperature
ambient temperature

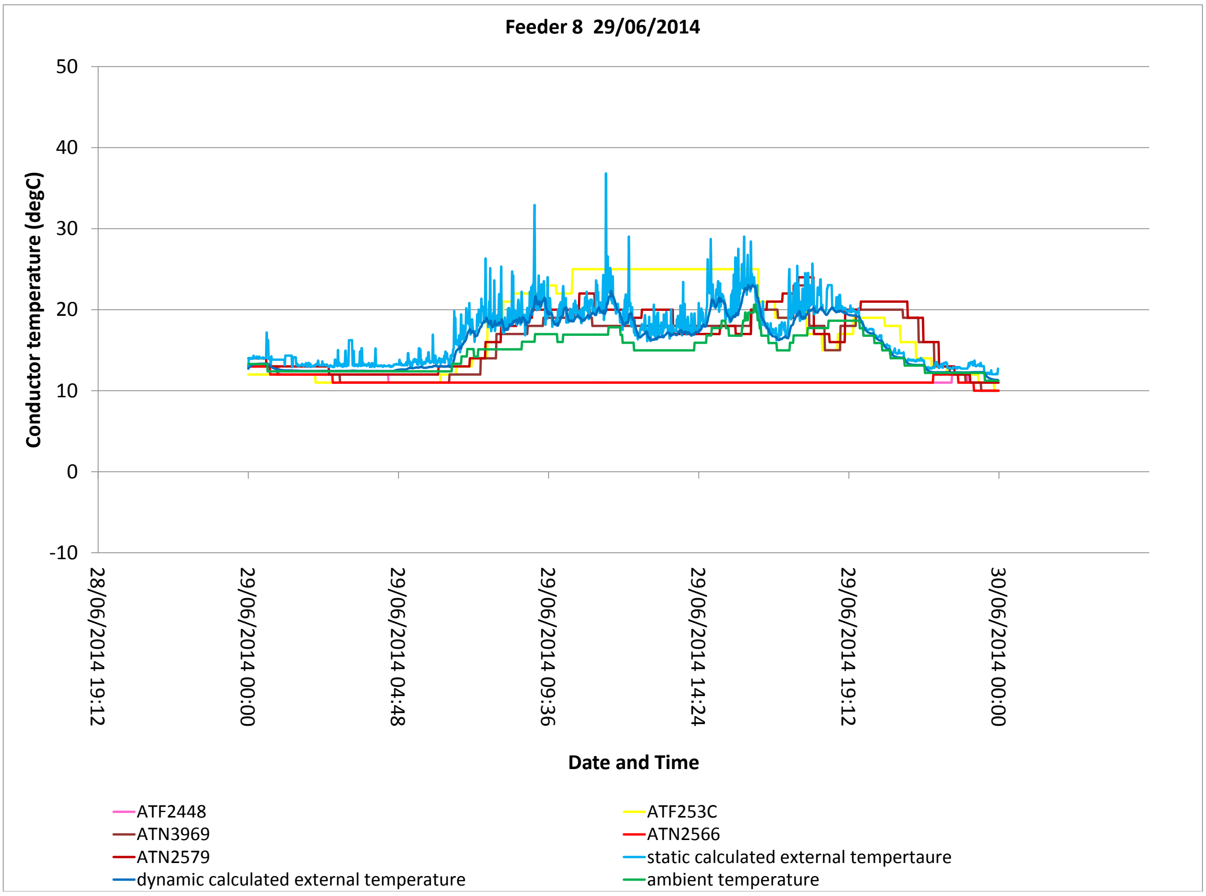


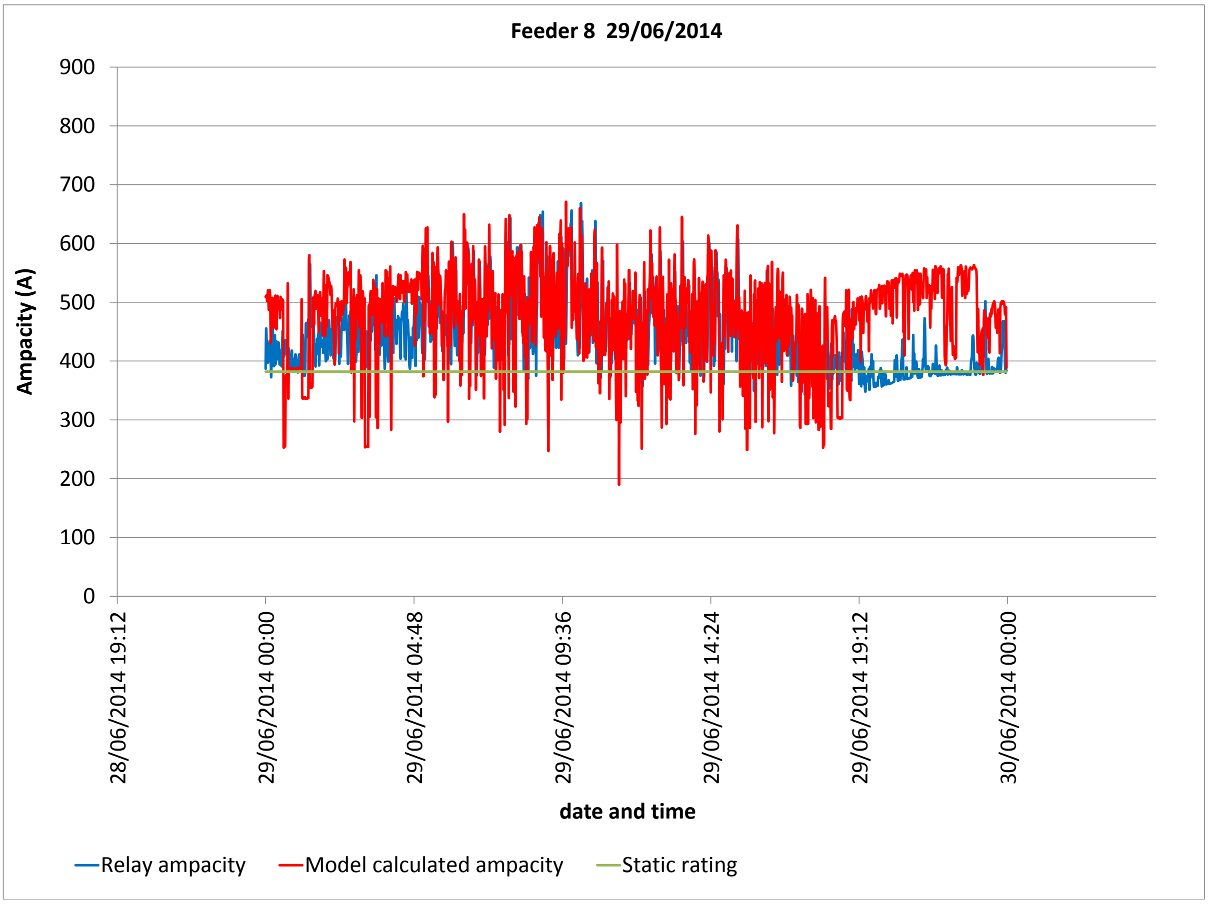
Feeder 4 : Spring Sunday 22/03/15, model calculated temperature against toll grade reported temperature, model calculated ampacity against relay calculated ampacity



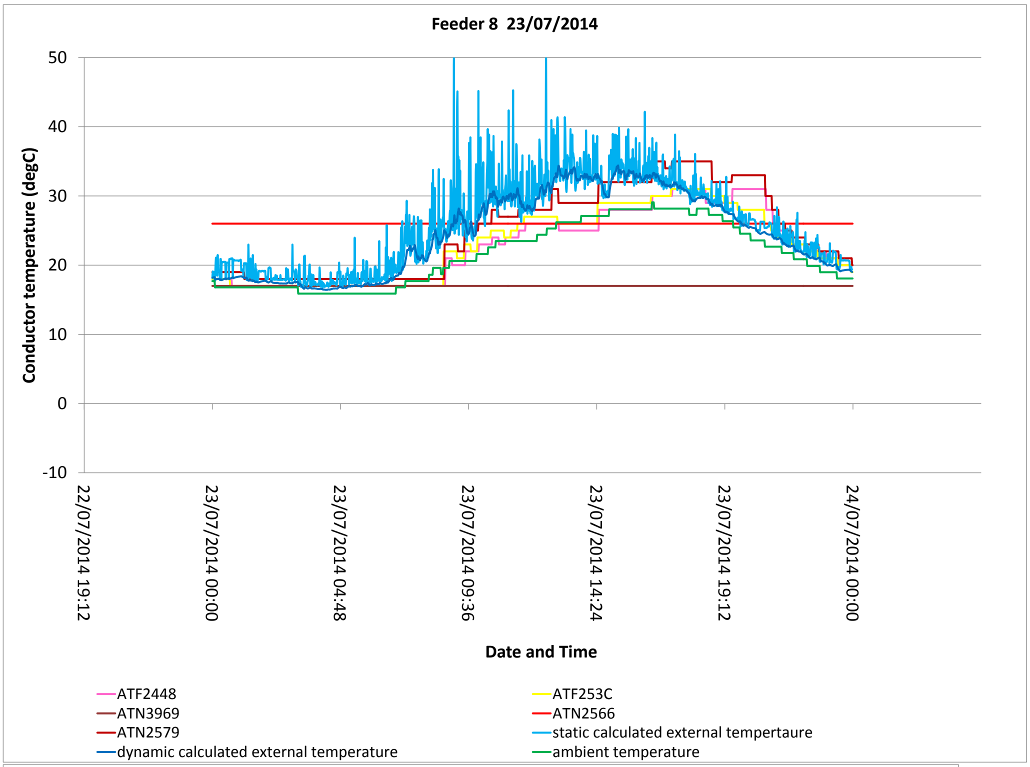


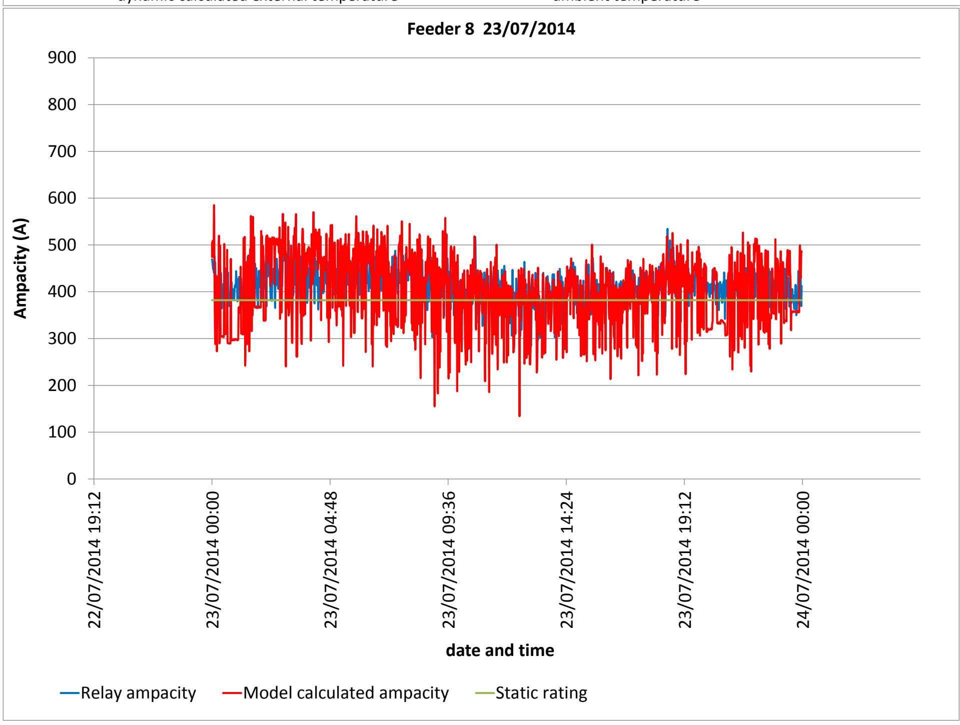
Feeder 8 : Summer Wednesday 25/06/14, model calculated temperature against toll grade reported temperature, model calculated ampacity against relay calculated ampacity


Feeder 8 29/06/2014
Conductor temperature (degC)
50
40
30
20
10
0
-10
28/06/2014 19:12
29/06/2014 00:00
29/06/2014 04:48
29/06/2014 09:36
29/06/2014 14:24
29/06/2014 19:12
30/06/2014 00:00
Date and Time
ATF2448
ATF253C
ATN3969
ATN2566
ATN2579
static calculated external tempertaure
dynamic calculated external temperature
ambient temperature

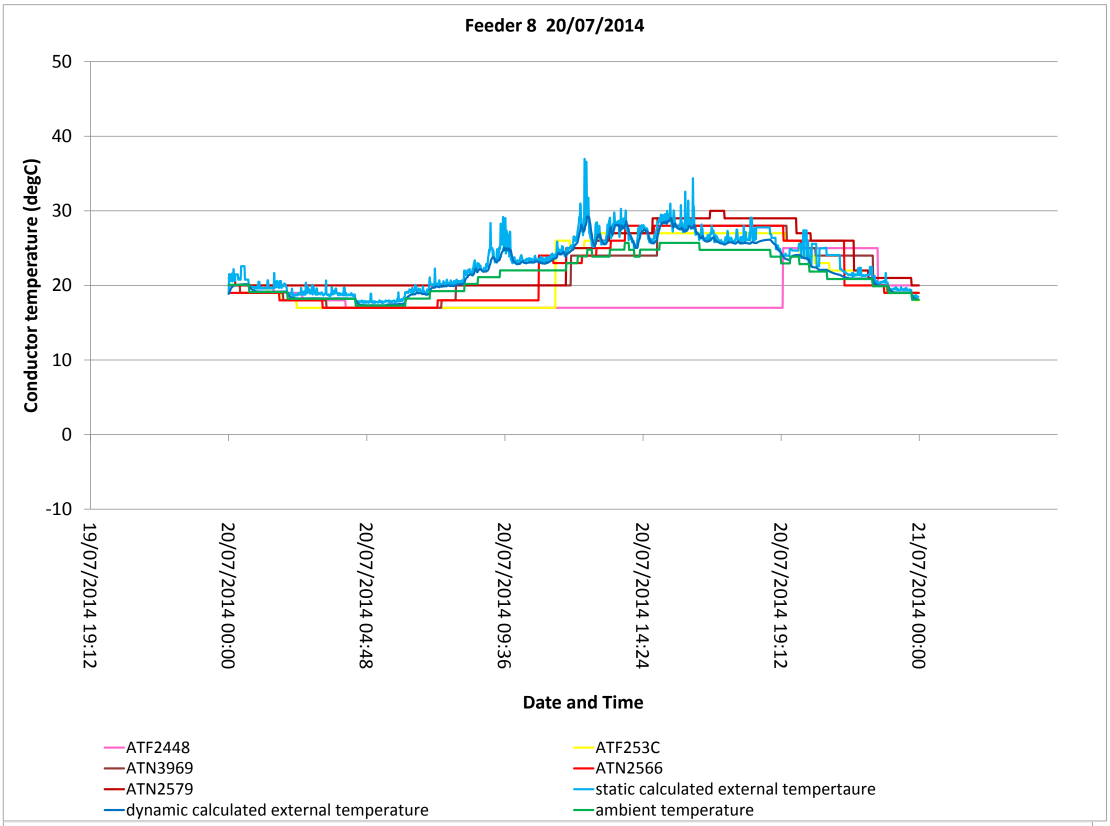


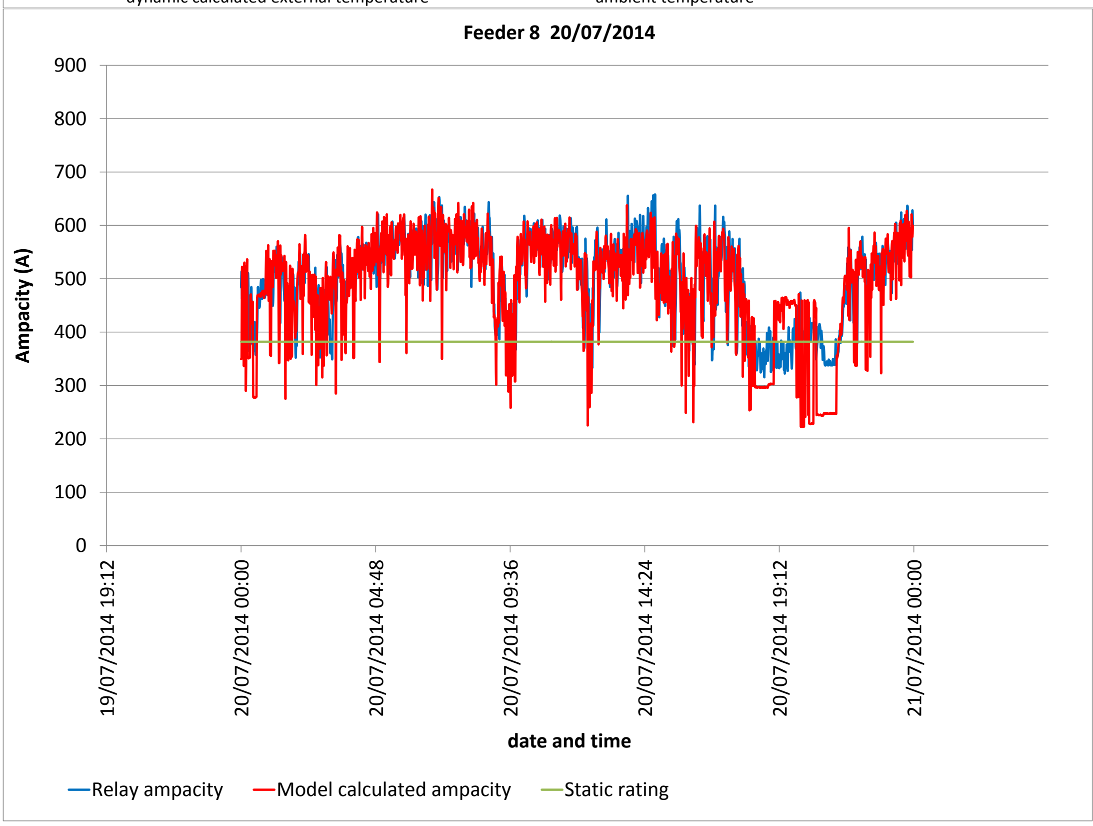
Feeder 8 : Summer Sunday 29/06/14, model calculated temperature against toll grade reported temperature, model calculated ampacity against relay calculated ampacity



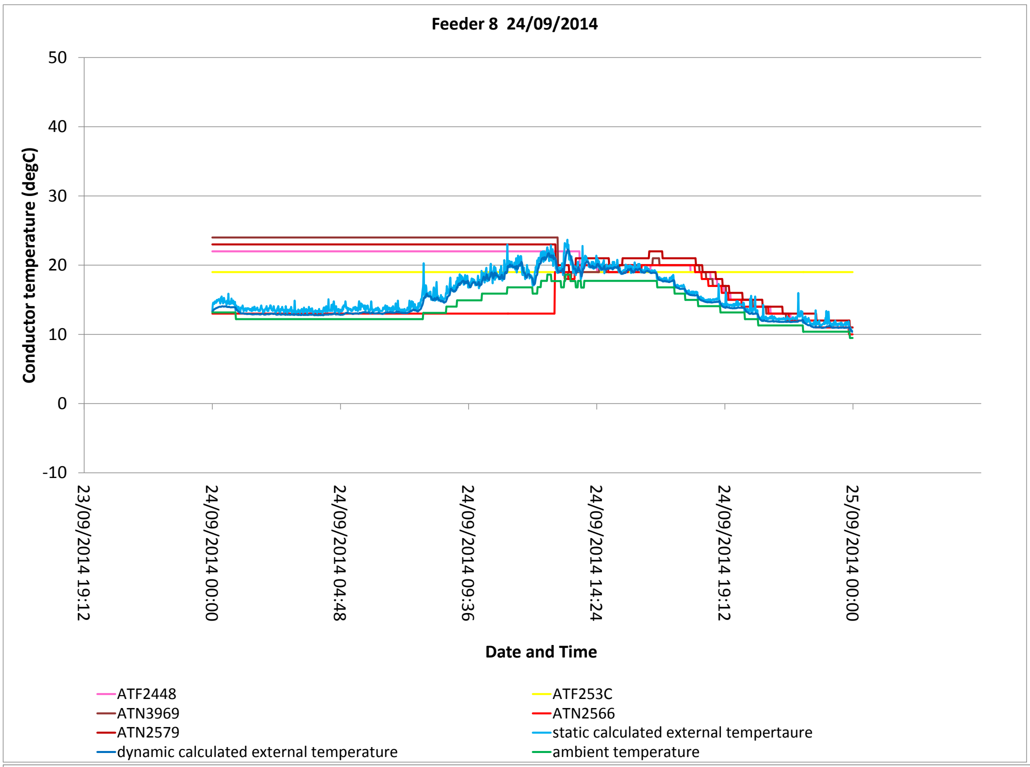


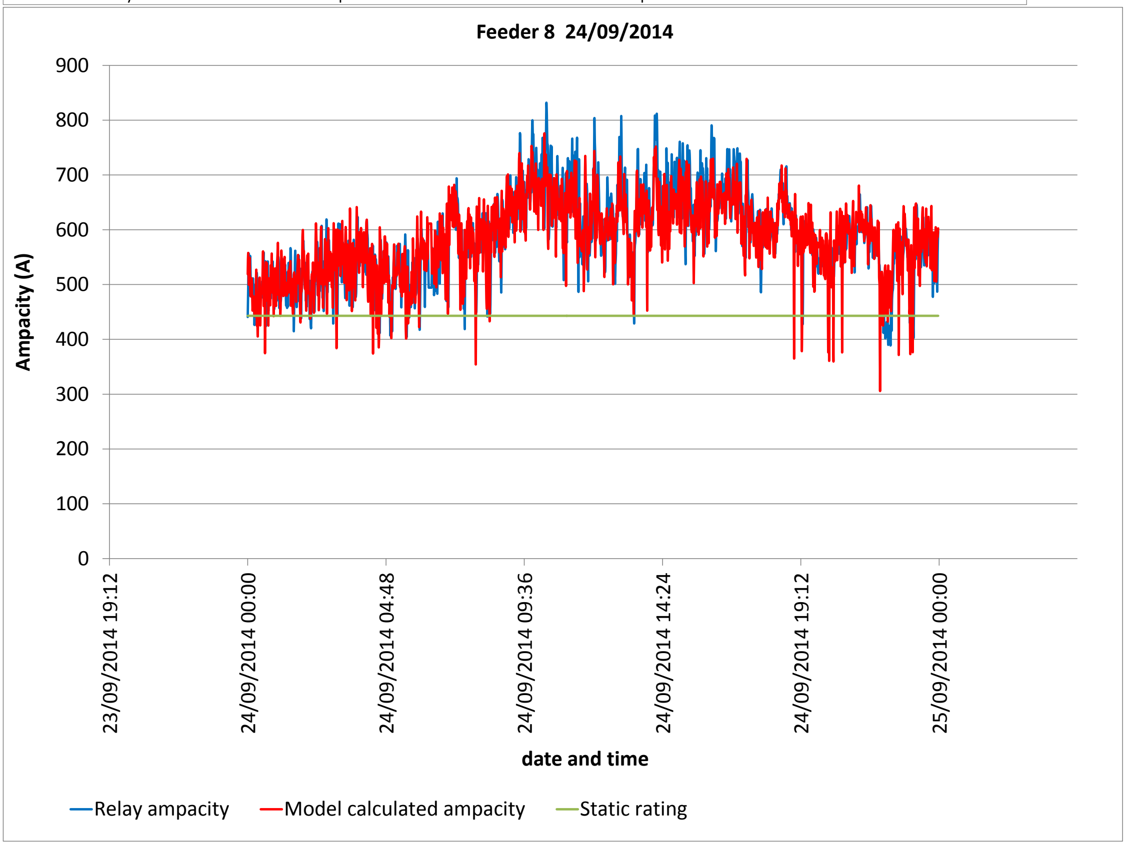
Feeder 8 : High Summer Wednesday 23/07/14, model calculated temperature against toll grade reported temperature, model calculated ampacity against relay calculated ampacity



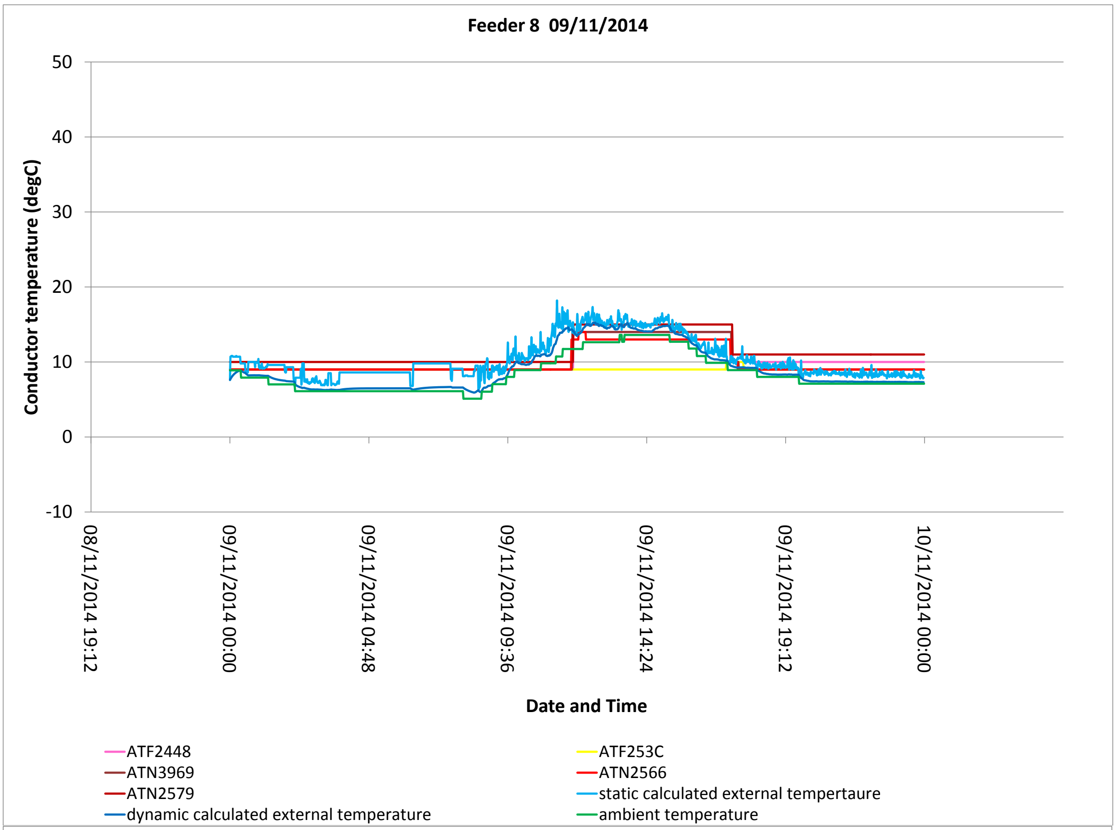


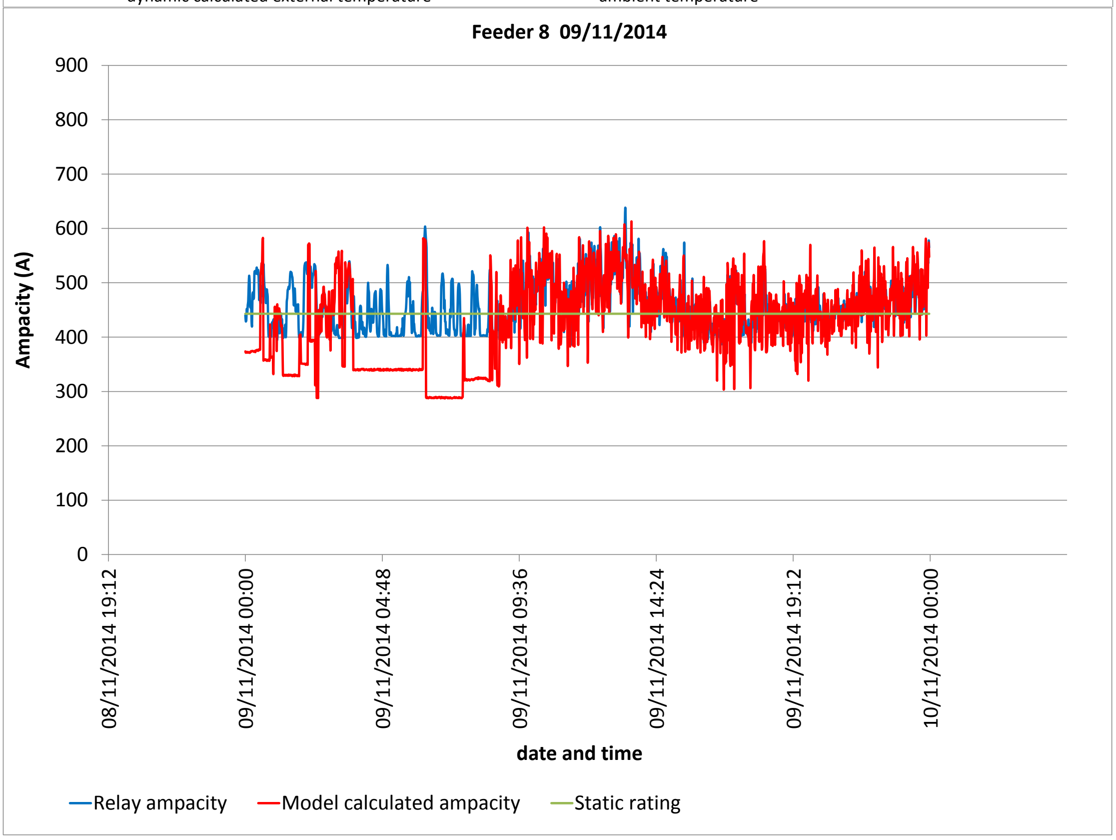
Feeder 8 : High Summer Sunday 20/07/14, model calculated temperature against toll grade reported temperature, model calculated ampacity against relay calculated ampacity





Feeder 8 : Autumn Wednesday 24/09/14, model calculated temperature against toll grade reported temperature, model calculated ampacity against relay calculated ampacity





Feeder 8 : Autumn Sunday 08/11/14, model calculated temperature against toll grade reported temperature, model calculated ampacity against relay calculated ampacity

J Predicted weather benefits

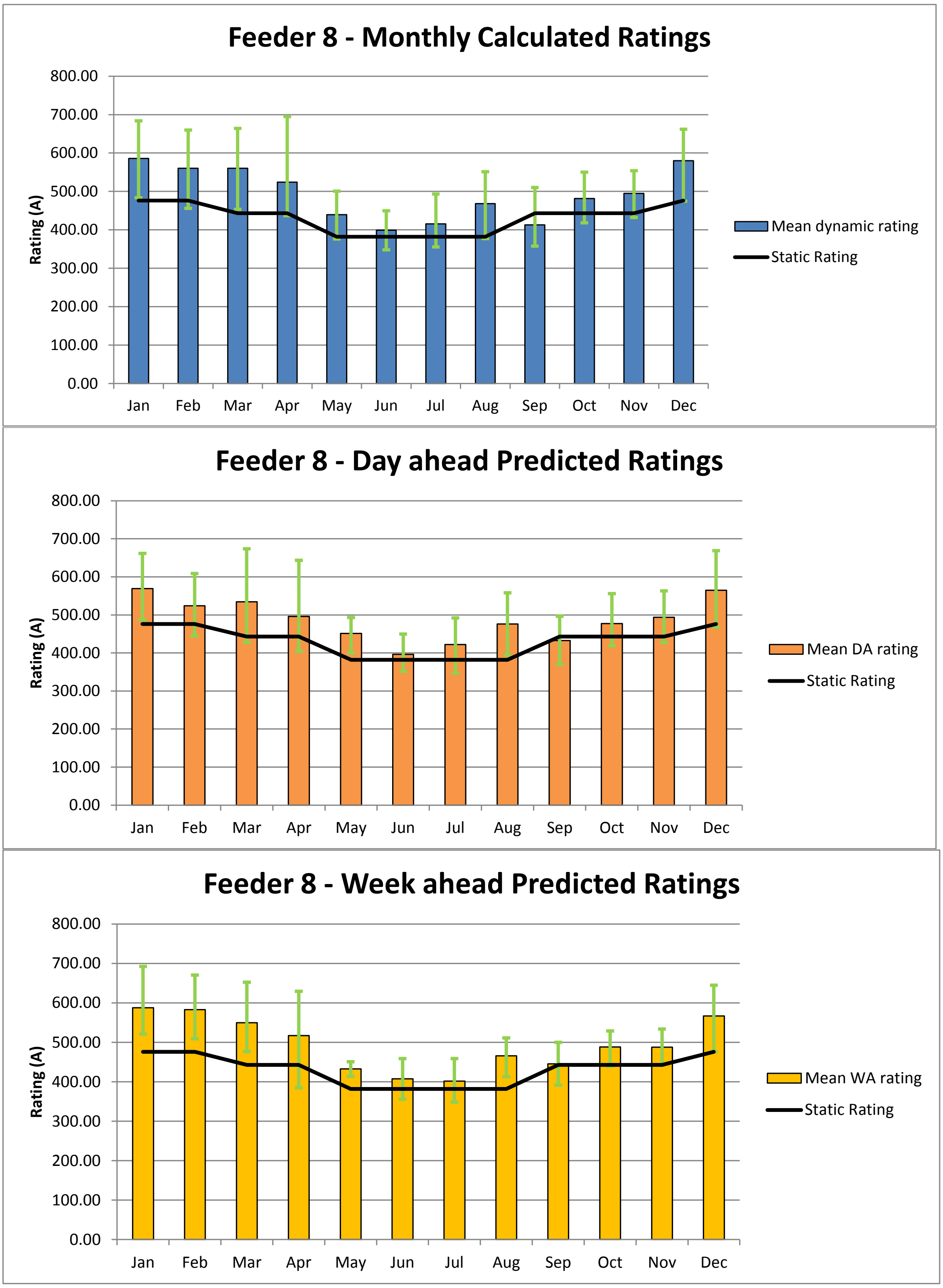


Figure 28 : Calculated Ampacity Benefits using a) measured data b) day ahead predicted data and c) week ahead predicted data for Feeder 8 over the course of a year

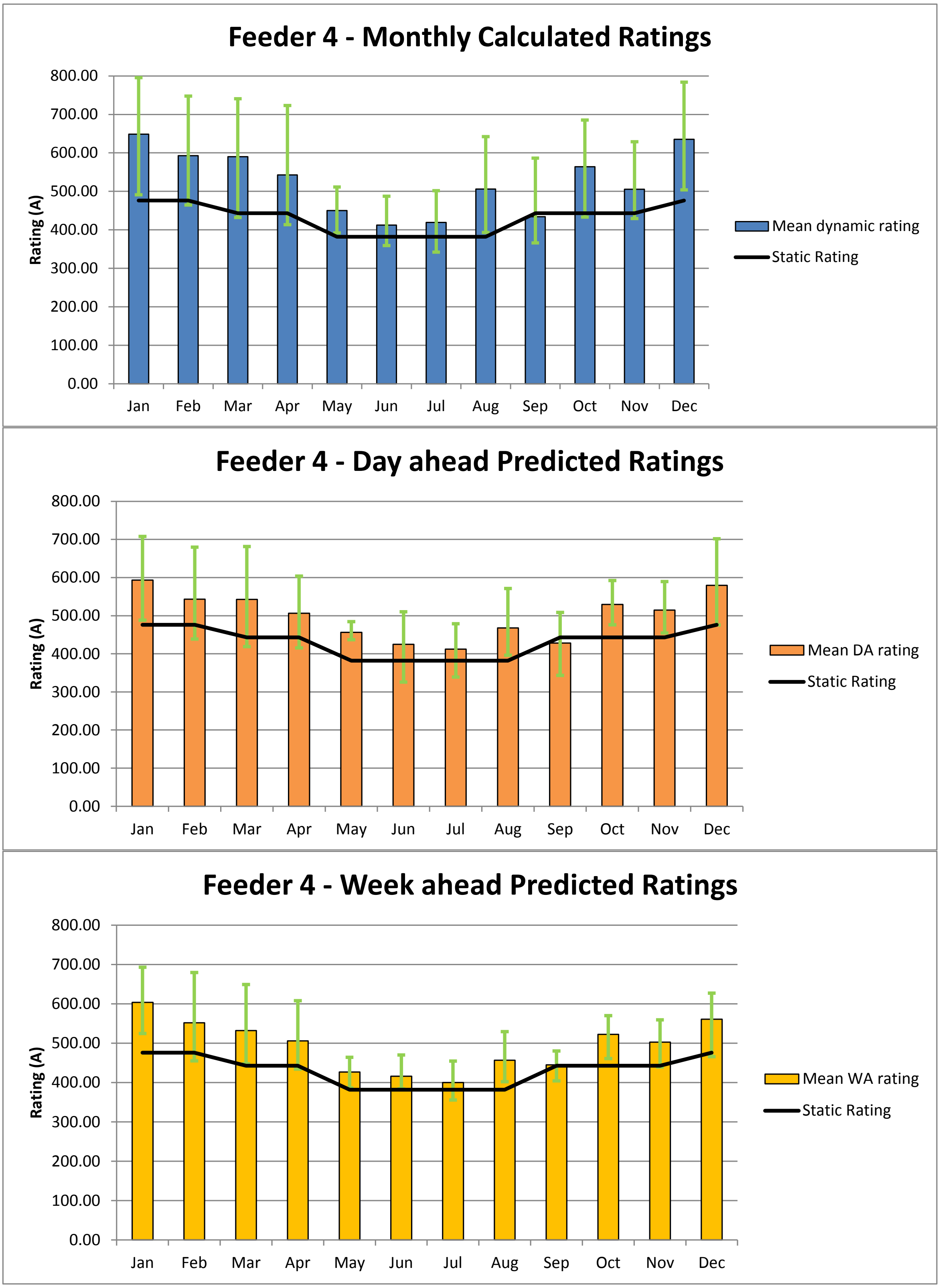


Figure 29 : Calculated Ampacity Benefits using a) measured data b) day ahead predicted data and c) week ahead predicted data for Feeder 4 over the course of a year

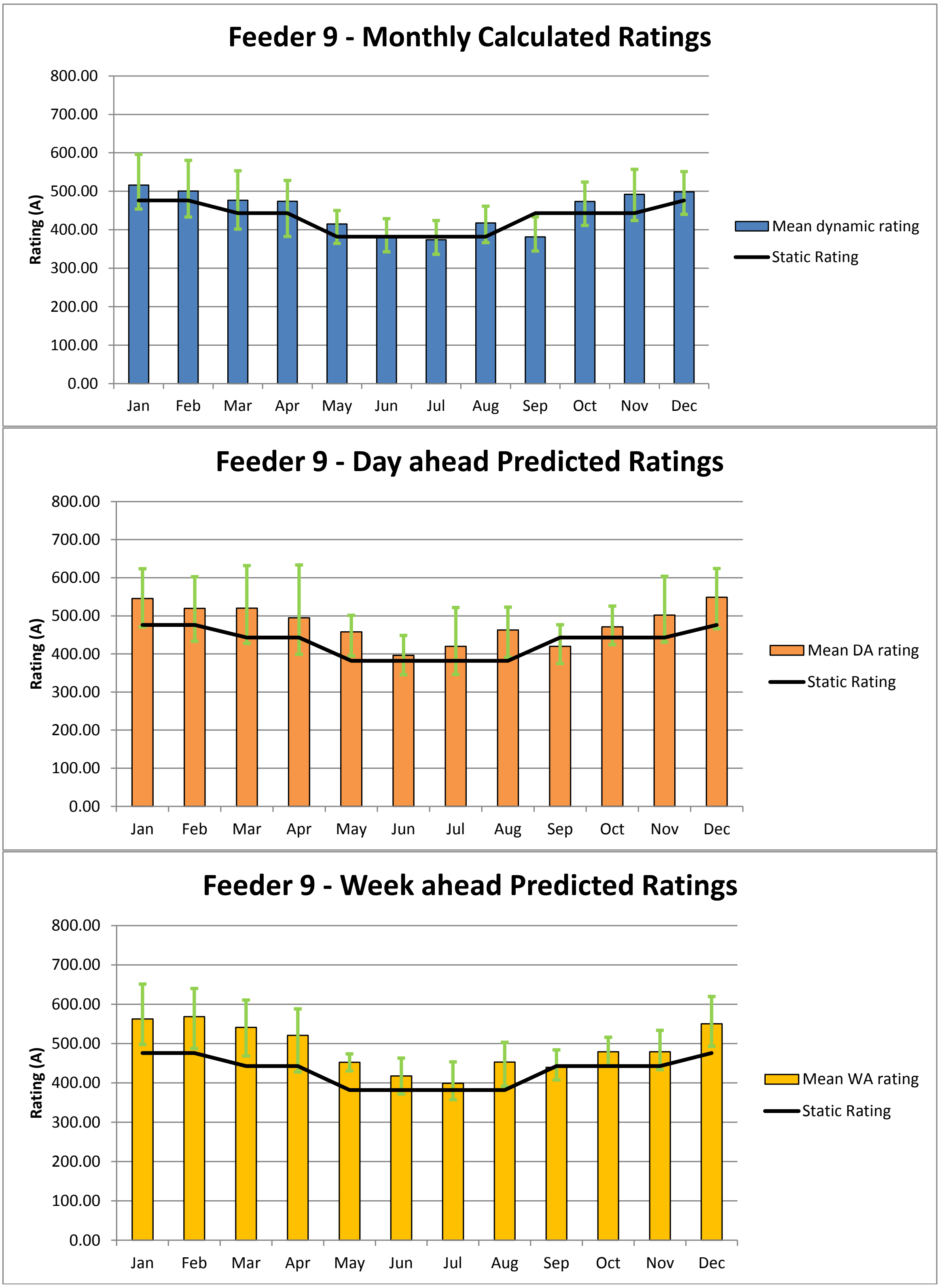
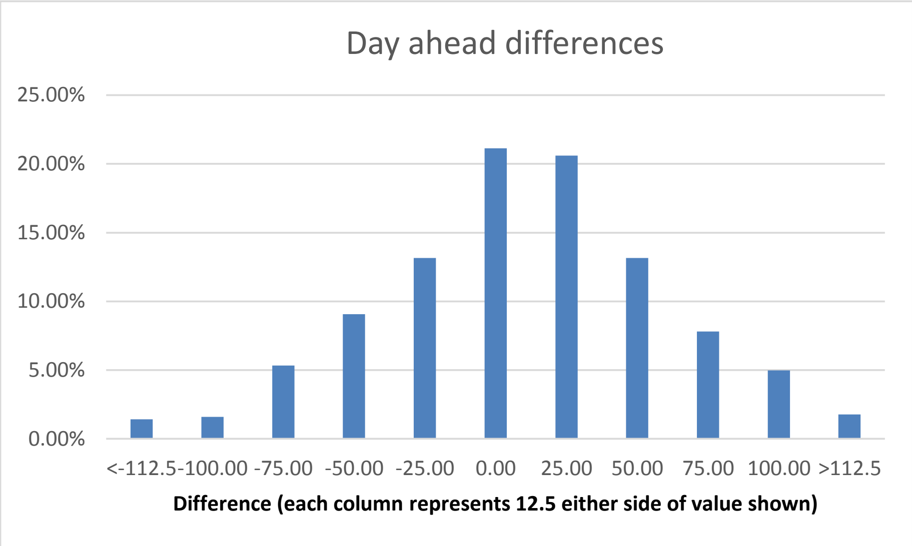


Figure 30 : Calculated Ampacity Benefits using a) measured data b) day ahead predicted data and c) week ahead predicted data for Feeder 9 over the course of a year

Although the benefits look similar there is a degree of uncertainty associated with the predicted data, which can result in the predicted ampacity being calculated as higher than the ampacity calculated on the same day using measured data. This inaccuracy in forecast data represents a risk to the operator. To quantify this risk the following approach was taken.

An error graph was produced by looking at the number of occurrences where predicted ampacity and calculated ampacity using measured data are different using only the good data sets. The graphs below show the error between measured and predicted data for each feeder. So for example, to guarantee that the predicted rating is always within 90% of that using the measured data on feeder 8 using the day ahead prediction, means that 75A has to me taken off the dynamic rating to ensure sufficient error margin.

The error charts allow an error margin to be set for each line based on required confidence level. So reducing the ampacity by a fixed value of Amps as shown below for each feeder allows the operator to be 90% confident that the ampacity calculated using predicted weather is within what would be calculated using measured data



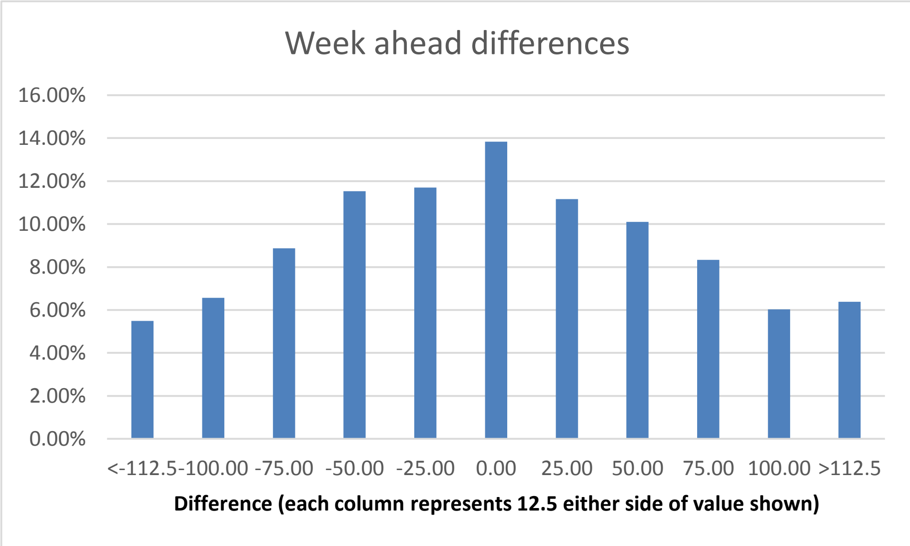
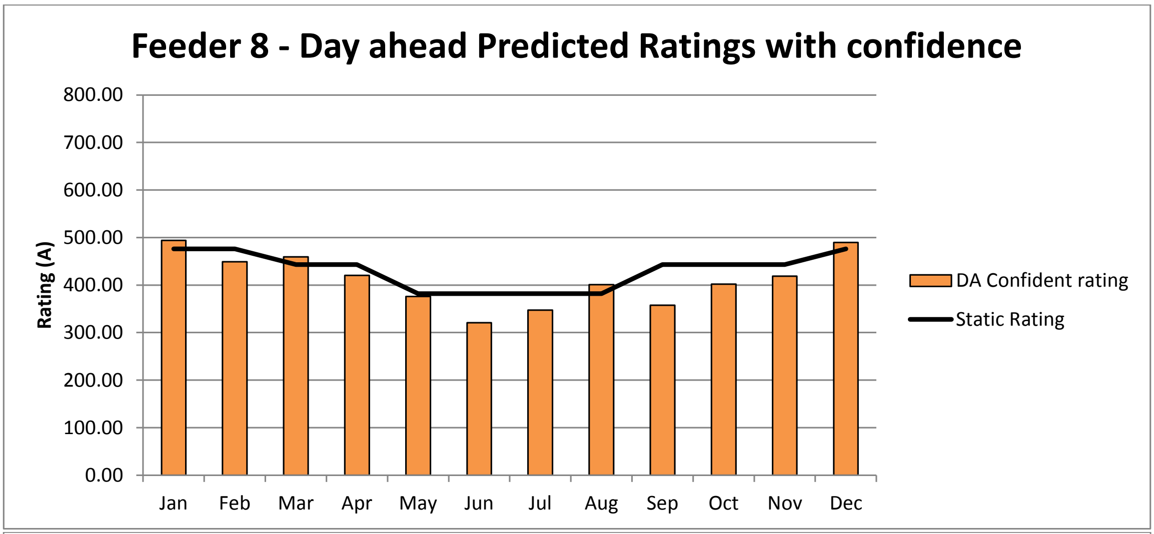


Figure 31 : Ampacity Error frequency plot on feeder 8 for a) day ahead predicted data vs measured data b) week ahead predicted data vs measured data



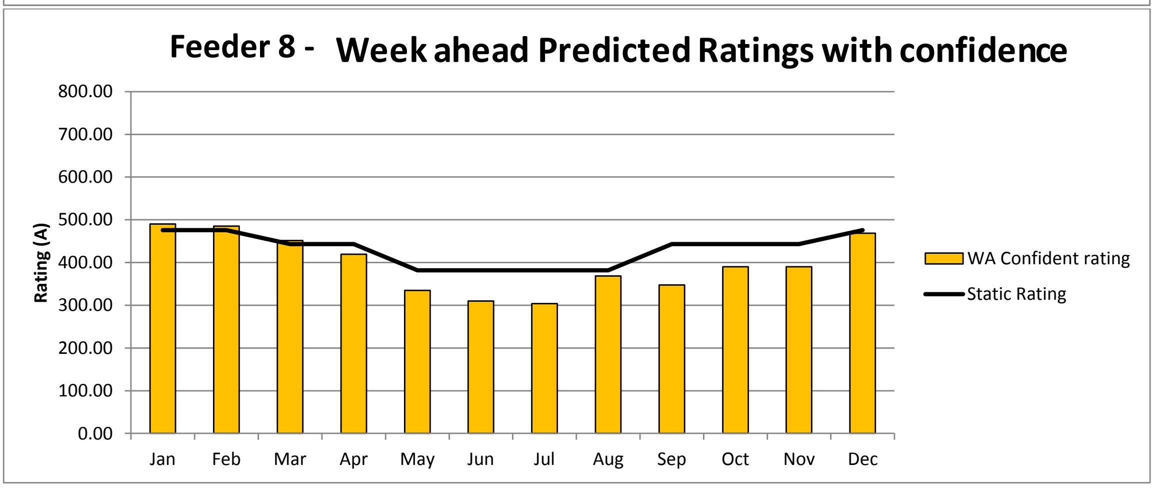
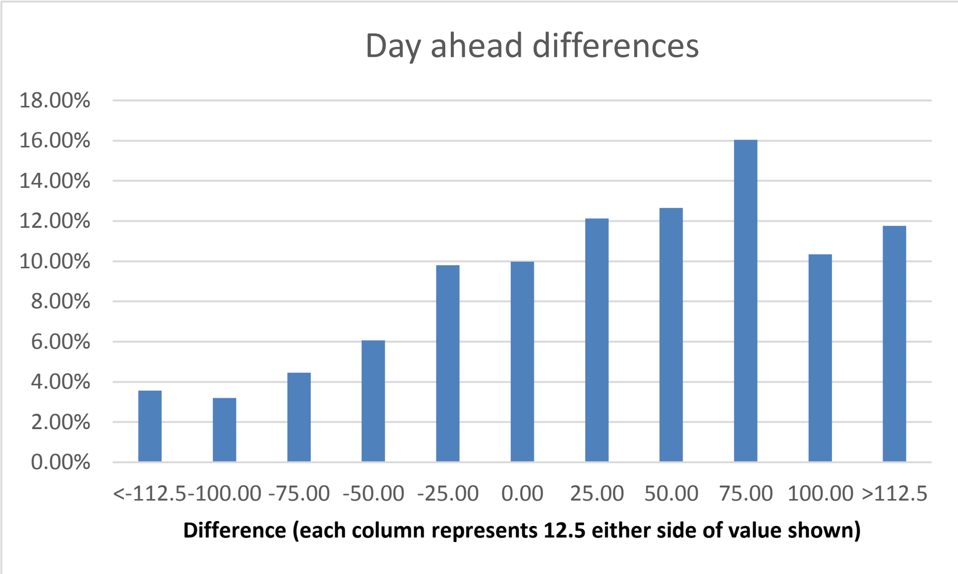


Figure 32 : 90% confidence calculated Ampacity Benefits using a) day ahead predicted data (75A) and b) week ahead predicted data (100A) for Feeder 8 over the course of a year with a 90% confidence level

LP 27.	It is harder to predict the rating of lines perpendicular to prevailing weather conditions as wind has more impact and the uncertainty in wind direction over a small time scale reduces the confidence level with which this can be calculated.

The prevailing wind speed is from the South west (approx. 220^{o}) see Figure 13. This hits line 4 closer to the perpendicular (134^{o}) than for the other two lines. Consequently because of the higher impact of wind direction near perpendicular, it means that the predicted rating on feeder 4 is harder to calculate with confidence and a greater error margin needs to be added.

Adding in a confidence margin significantly reduces the benefits available to the operator to the months of Dec and Jan. The greater uncertainty in the week ahead calculation results in still lower determined capacity headroom benefit.



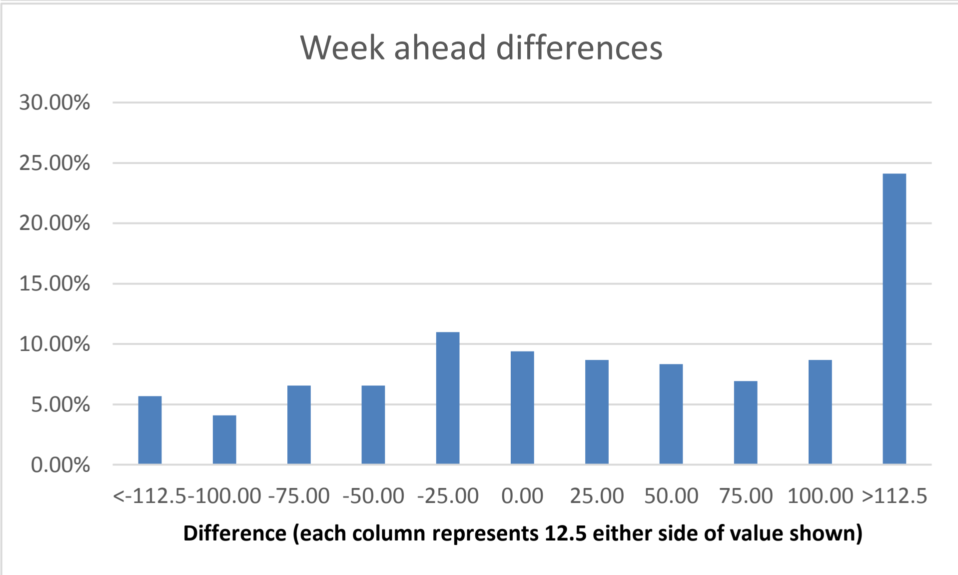
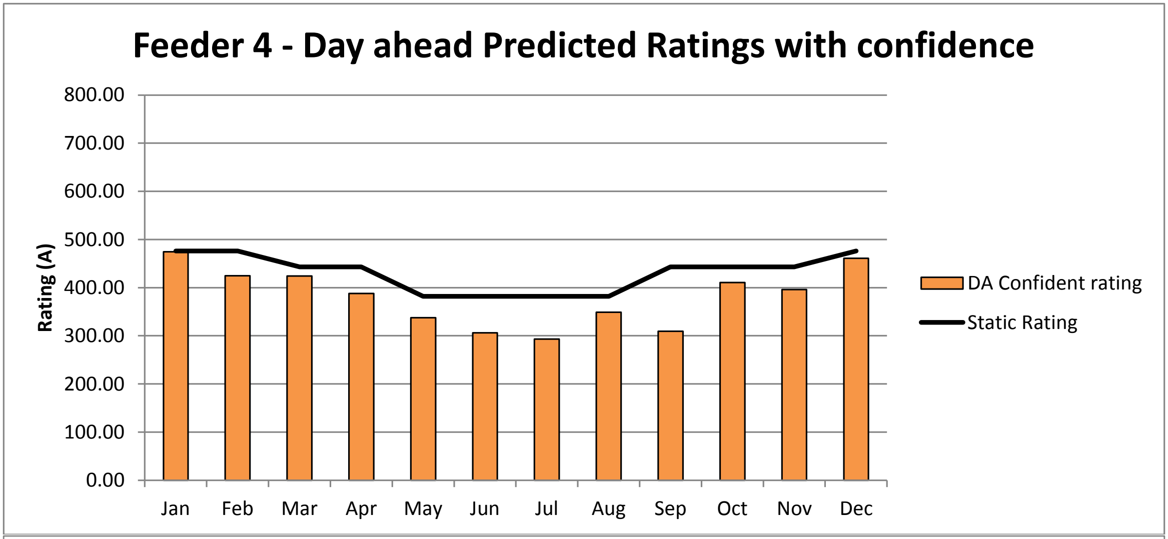


Figure 33 : Ampacity Error frequency plot on feeder 4 for a) day ahead predicted data vs measured data b) week ahead predicted data vs measured data



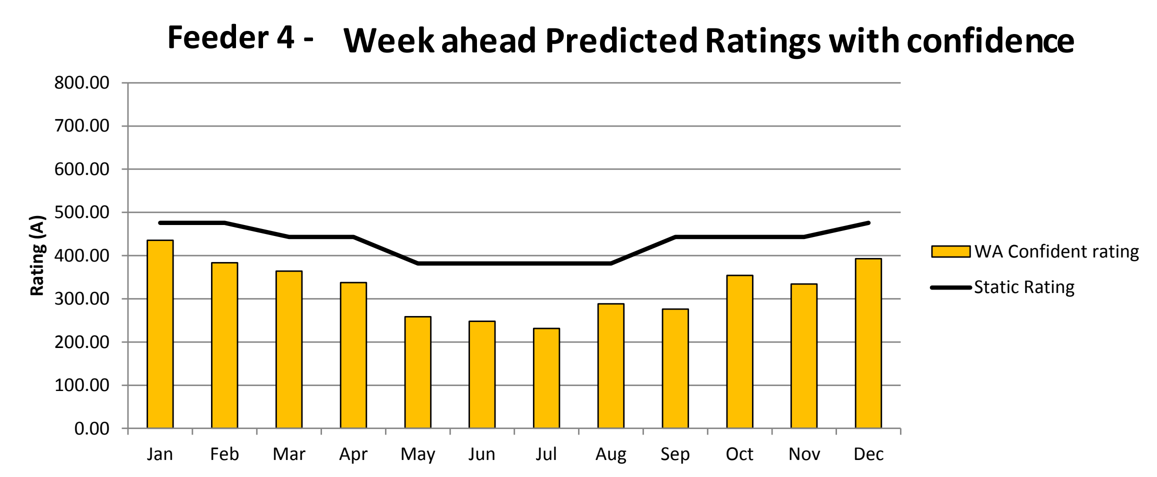
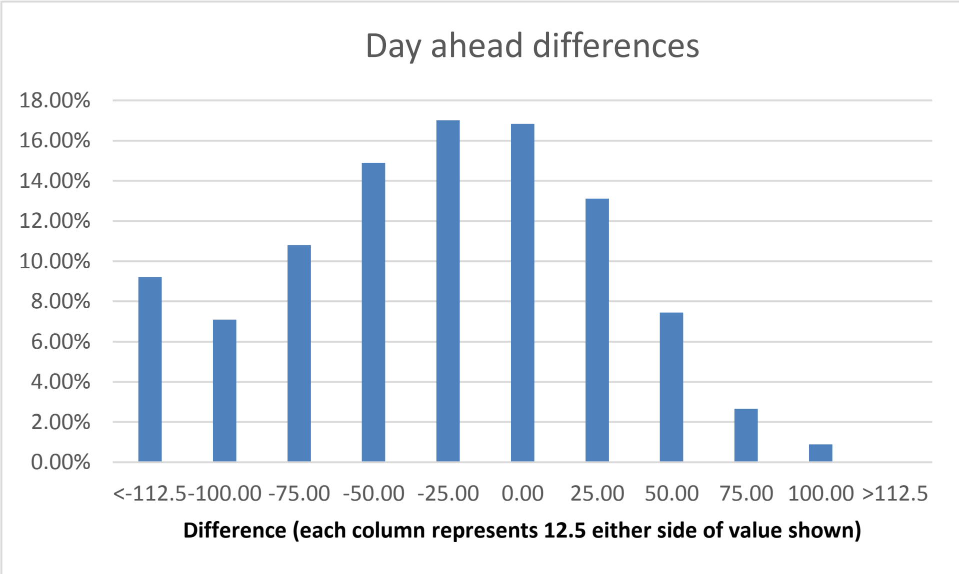


Figure 34 : 90% confidence calculated Ampacity Benefits using a) day ahead predicted data (120A) and b) week ahead predicted data (170A) for Feeder 4 over the course of a year with a 90% confidence level



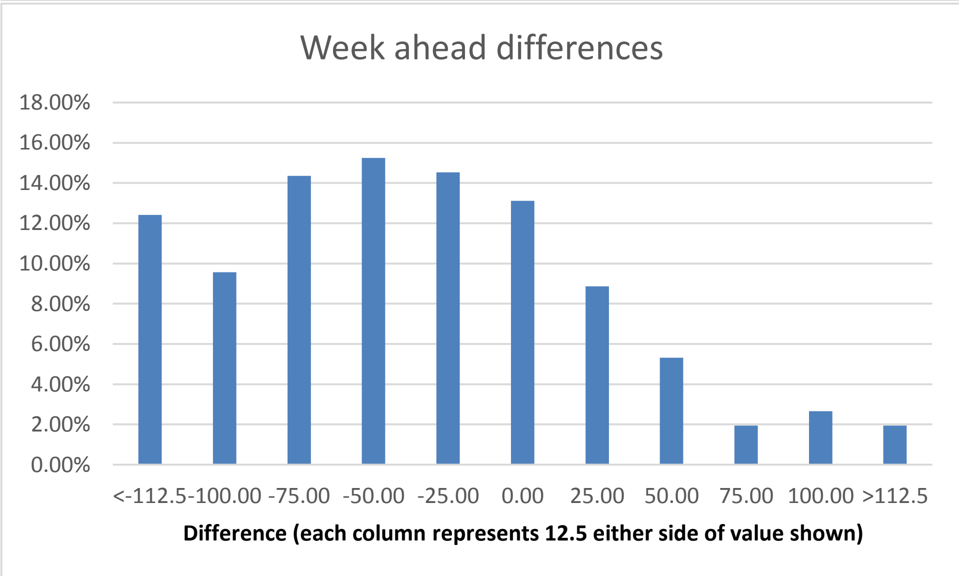


Figure 35 : Ampacity Error frequency plot on feeder 9for a) day ahead predicted data vs measured data b) week ahead predicted data vs measured data

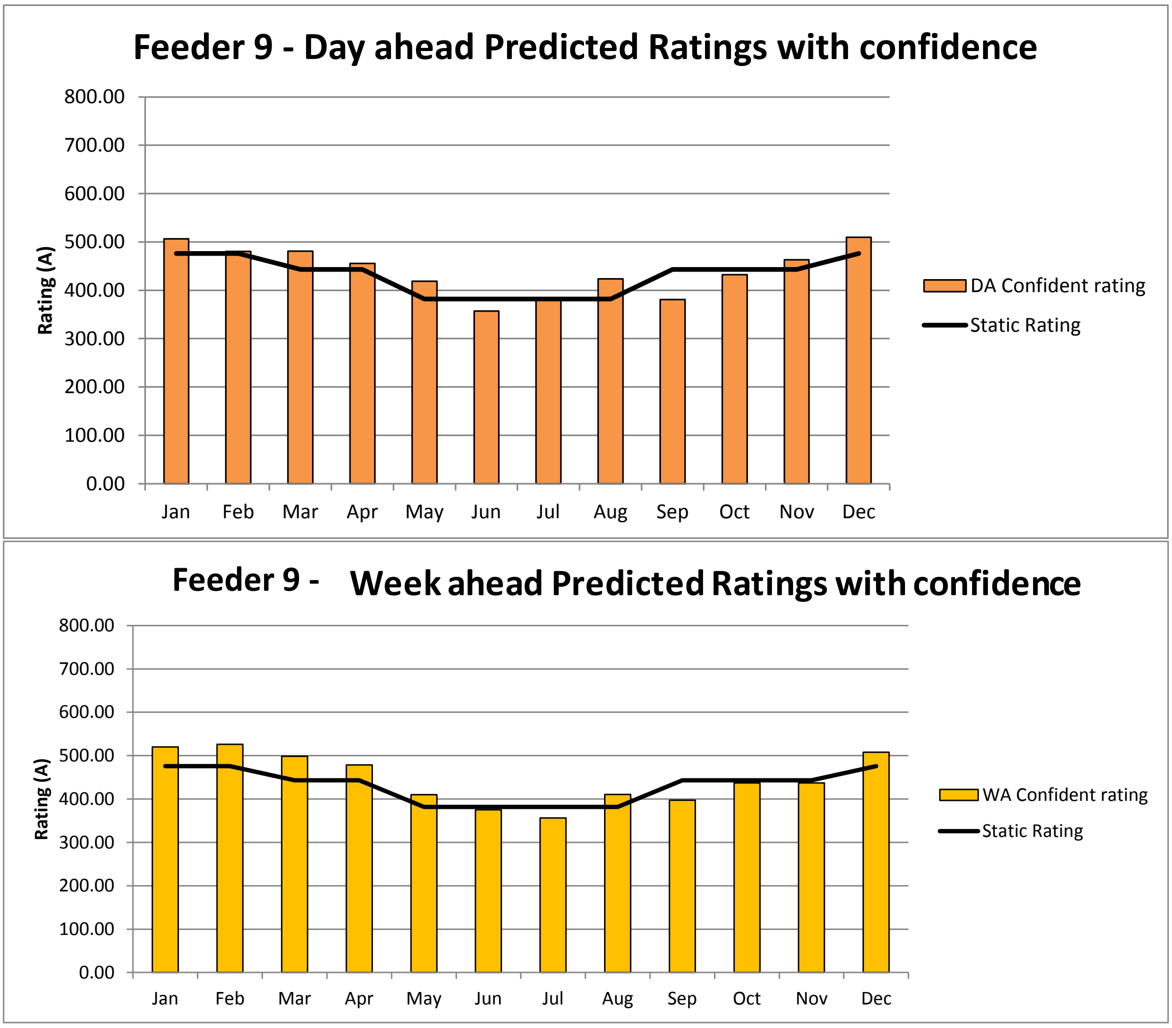


Figure 36 : 90% confidence calculated Ampacity Benefits using a) day ahead predicted data (40A) and b) week ahead predicted data (40A) for Feeder 9 over the course of a year with a 90% confidence level

K Weather Prediction download code

```
<?php

date_default_timezone_set('Europe/London');

header('Content-Type: text/plain');

$base_url = "http://www.bbc.co.uk/weather/en/2642465/daily/" . date('Y-m-d');

$ch = curl_init($base_url . '?day=1');

curl_setopt($ch,CURLOPT_RETURNTRANSFER,true);

$page = curl_exec($ch);

curl_close($ch);

$mysqli = new mysqli("localhost", "pm1nps_weather", "AtAp2zJVuGmJPacR",
"pm1nps_weather");

if ($mysqli->connect_errno) {

 echo "Failed to connect to MySQL: (" . $mysqli->connect_errno . ") " . $mysqli-
>connect_error;

}

$doc = new DOMDocument();

@ $doc->loadHTML($page);

$caption = xpath_text("//*[@id=\"hourly\"]/div[3]/table/caption",$doc);

$t1 = '//*[@id="hourly"]/div[3]/table/thead/tr/th[2]/span[1]';

$t2 = '//*[@id="hourly"]/div[3]/table/thead/tr/th[3]/span[1]';

$cc = array();

$last_time = 0;

$time_shift = 0;

for ($i = 0; $i < 24; $i++) {

 $i1 = $i+1;

 $i2 = $i+2;

 $c = new stdClass();
```

```
$c->forecast_date = date('Y-m-d');

$c->target_date = date('Y-m-d',time() + 24*3600);

$c->hour =
xpath_text("//*[@id=\"hourly\"]/div[3]/table/thead/tr/th[$i2]/span[1]",$doc);

if ($c->hour === false || $c->hour === '') { break; }

$c->hour = $time_shift + (int) $c->hour;

if ($last_time == 23 && $c->hour == 0) {

 $time_shift = 24;

 $c->hour = 24;

}

$e = xpath_node("//*[@id=\"hourly\"]/div[3]/table/tbody/tr[1]/td[$i1]/span/img",$doc);

$c->conditions = $e->getAttribute("alt");

$c->temperature =

 wrap_int(xpath_text("//*[@id=\"hourly\"]/div[3]/table/tbody/tr[2]/td[$i1]/span/span/s
pan[1]/text()",$doc));

$c->wind_speed =

 wrap_int(xpath_text("//*[@id=\"hourly\"]/div[3]/table/tbody/tr[3]/td[$i1]/span/span[1
]/span/span[1]/text()",$doc));

$c->wind_direction =

 xpath_text("//*[@id=\"hourly\"]/div[3]/table/tbody/tr[4]/td[$i1]/abbr",$doc);

$c->humidity =

 wrap_int(trim(xpath_text("//*[@id=\"hourly\"]/div[3]/table/tfoot/tr[1]/td[$i1]/text()",$
doc),'%'));

$c->visibility =

 xpath_text("//*[@id=\"hourly\"]/div[3]/table/tfoot/tr[2]/td[1]/abbr",$doc);

$c->pressure =

 wrap_int(xpath_text("//*[@id=\"hourly\"]/div[3]/table/tfoot/tr[3]/td[1]/text()",$doc));

$cc[] = $c;
```

```
 $last_time = $c->hour;
}
foreach ($cc as $c) {
 echo
  $c->hour . ',' .
  '"' . $c->conditions . '",' .
  $c->temperature . ',' .
  $c->wind_speed . ',' .
  '"' . $c->wind_direction . '",' .
  $c->humidity . ',' .
  '"' . $c->visibility . '",' .
  $c->pressure . "\n";
 $sql = <<<SQL
 INSERT INTO tbl_immediate(forecast_date,target_date,hour,conditions,temperature,
                    wind_speed,wind_direction,humidity,visibility,pressure)
 VALUES ('{$c->forecast_date}','{$c->target_date}',{$c->hour},'{$c->conditions}',
        {$c->temperature},{$c->wind_speed},'{$c->wind_direction}',
        {$c->humidity},'{$c->visibility}',{$c->pressure})
SQL;
 if (! $mysqli->query($sql)) {
  echo "Save failed: (" . $mysqli->errno . ") " . $mysqli->error;
 }
}
echo "\n\n\n\n";
$page = file_get_contents($base_url . '?day=7');
$doc = new DOMDocument();
@ $doc->loadHTML($page);
```

```
$caption = xpath_text("//*[@id=\"hourly\"]/div[3]/table/caption",$doc);

$t1 = '//*[@id="hourly"]/div[3]/table/thead/tr/th[2]/span[1]';

$t2 = '//*[@id="hourly"]/div[3]/table/thead/tr/th[3]/span[1]';

$cc = array();

$last_time = 0;

$time_shift = 0;

$c = new stdClass();

$c->forecast_date = date('Y-m-d');

$c->target_date = date('Y-m-d',time() + (7*24+2)*3600);

$e = xpath_node("//*[@id=\"hourly\"]/div[3]/table/tbody/tr[1]/td[1]/span/img",$doc);

$c->day_conditions = $e->getAttribute("alt");

$c->day_temperature_min =

 wrap_int(xpath_text("//*[@id=\"hourly\"]/div[3]/table/tbody/tr[2]/td[1]/span/span[2]/span/span[1]/text()",$doc));

$c->day_temperature_max =

 wrap_int(xpath_text("//*[@id=\"hourly\"]/div[3]/table/tbody/tr[2]/td[1]/span/span[3]/span/span[1]/text()",$doc));

$c->day_wind_speed =

 wrap_int(xpath_text("//*[@id=\"hourly\"]/div[3]/table/tbody/tr[3]/td[1]/span/span[1]/span/span[1]/text()",$doc));

$c->day_wind_direction =

 xpath_text("//*[@id=\"hourly\"]/div[3]/table/tbody/tr[4]/td[1]/abbr",$doc);

$c->day_humidity =

 wrap_int(trim(xpath_text("//*[@id=\"hourly\"]/div[3]/table/tfoot/tr[1]/td[1]/text()",$doc),'%'));

$c->day_visibility =

 xpath_text("//*[@id=\"hourly\"]/div[3]/table/tfoot/tr[2]/td[1]/abbr",$doc);

$c->day_pressure =
```

```
 wrap_int(xpath_text("//*[@id=\"hourly\"]/div[3]/table/tfoot/tr[3]/td[1]/text()",$doc));

$e = xpath_node("//*[@id=\"hourly\"]/div[3]/table/tbody/tr[1]/td[2]/span/img",$doc);

$c->night_conditions = $e->getAttribute("alt");

$c->night_temperature_min =

 wrap_int(xpath_text("//*[@id=\"hourly\"]/div[3]/table/tbody/tr[2]/td[2]/span/span[2]/s
pan/span[1]/text()",$doc));

$c->night_temperature_max =

 wrap_int(xpath_text("//*[@id=\"hourly\"]/div[3]/table/tbody/tr[2]/td[2]/span/span[3]/s
pan/span[1]/text()",$doc));

$c->night_wind_speed =

 wrap_int(xpath_text("//*[@id=\"hourly\"]/div[3]/table/tbody/tr[3]/td[2]/span/span[1]/s
pan/span[1]/text()",$doc));

$c->night_wind_direction =

 xpath_text("//*[@id=\"hourly\"]/div[3]/table/tbody/tr[4]/td[2]/abbr",$doc);

$c->night_humidity =

 wrap_int(trim(xpath_text("//*[@id=\"hourly\"]/div[3]/table/tfoot/tr[1]/td[2]/text()",$do
c),'%'));

$c->night_visibility =

 xpath_text("//*[@id=\"hourly\"]/div[3]/table/tfoot/tr[2]/td[2]/abbr",$doc);

$c->night_pressure =

 wrap_int(xpath_text("//*[@id=\"hourly\"]/div[3]/table/tfoot/tr[3]/td[2]/text()",$doc));

echo

  '"' . $c->day_conditions . '",' .

  $c->day_temperature_min . ',' .

  $c->day_temperature_max . ',' .

  $c->day_wind_speed . ',' .

  '"' . $c->day_wind_direction . '",' .

  $c->day_humidity . ',' .
```

```
 '"' . $c->day_visibility . '",' .
 $c->day_pressure . ',' .
 '"' . $c->night_conditions . '",' .
 $c->night_temperature_min . ',' .
 $c->night_temperature_max . ',' .
 $c->night_wind_speed . ',' .
 '"' . $c->night_wind_direction . '",' .
 $c->night_humidity . ',' .
 '"' . $c->night_visibility . '",' .
 $c->night_pressure . "\n";
$sql = <<<SQL
 INSERT INTO tbl_delayed(forecast_date,target_date,
                    day_conditions,day_temperature_min,day_temperature_max,
                    day_wind_speed,day_wind_direction,day_humidity,day_visibility,day_pressur
e,
                    night_conditions,night_temperature_min,night_temperature_max,
                    night_wind_speed,night_wind_direction,night_humidity,night_visibility,night
_pressure)
 VALUES ('{$c->forecast_date}','{$c->target_date}',
         '{$c->day_conditions}',{$c->day_temperature_min},{$c->day_temperature_max},
         {$c->day_wind_speed},'{$c->day_wind_direction}',{$c->day_humidity},'{$c-
>day_visibility}',{$c->day_pressure},
         '{$c->night_conditions}',{$c->night_temperature_min},{$c-
>night_temperature_max},
         {$c->night_wind_speed},'{$c->night_wind_direction}',{$c->night_humidity},'{$c-
>night_visibility}',{$c->night_pressure})
SQL;
 if (! $mysqli->query($sql)) {
  echo "Save failed: (" . $mysqli->errno . ") " . $mysqli->error . "\n\n" . $sql;
```

```
 }
exit;
////////////////////////////////////////////////////////////////////////
function xpath_node($p,$d) {
 $x = new DOMXpath($d);
 $ee = $x->query($p);
 if ($ee->length != 1) { return false; }
 return $ee->item(0);
}
function xpath_text($p,$d) {
 $e = xpath_node($p,$d);
 return $e ? trim($e->textContent) : false;
}
function wrap_int($x) {
 if (preg_match("/^-?[1-9][0-9]*$/D", $x)) {
  return($x);
 } else {
  return 'NULL';
 }
}
?>
```

L An example of downloaded predicted weather data

forecast_date	target_date	hour	Target_TimeDate	conditions	temperature	wind_speed	wind_direction	humidity	visibility	pressure	W_Spd_m/s
26/07/2014	27/07/2014	24	28/07/2014 00:00	Partly Cloudy	16	8	NW	77	VG	1016	3.58
26/07/2014	27/07/2014	25	28/07/2014 01:00	Partly Cloudy	15	8	NW	81	VG	1016	3.58
26/07/2014	27/07/2014	28	28/07/2014 04:00	Light Cloud	15	6	WNW	83	VG	1016	2.68
27/07/2014	28/07/2014	6	28/07/2014 06:00	Light Cloud	15	10	NNW	79	VG	1015	4.47
27/07/2014	28/07/2014	7	28/07/2014 07:00	Light Cloud	15	10	NNW	81	VG	1015	4.47
27/07/2014	28/07/2014	8	28/07/2014 08:00	Light Cloud	16	8	N	78	VG	1015	3.58
27/07/2014	28/07/2014	9	28/07/2014 09:00	Sunny Intervals	17	10	N	72	VG	1015	4.47
27/07/2014	28/07/2014	10	28/07/2014 10:00	Sunny	18	10	NNE	66	VG	1015	4.47
27/07/2014	28/07/2014	11	28/07/2014 11:00	Sunny Intervals	18	10	NNE	61	VG	1015	4.47
27/07/2014	28/07/2014	12	28/07/2014 12:00	Sunny Intervals	19	11	NNE	57	VG	1015	4.92
27/07/2014	28/07/2014	13	28/07/2014 13:00	Light Cloud	20	11	NE	53	VG	1015	4.92
27/07/2014	28/07/2014	14	28/07/2014 14:00	Sunny Intervals	21	11	NE	51	VG	1015	4.92
27/07/2014	28/07/2014	15	28/07/2014 15:00	Sunny Intervals	21	10	NE	50	VG	1015	4.47
27/07/2014	28/07/2014	16	28/07/2014 16:00	Sunny Intervals	22	10	NE	48	VG	1015	4.47
27/07/2014	28/07/2014	17	28/07/2014 17:00	Sunny Intervals	22	10	NE	49	VG	1015	4.47
27/07/2014	28/07/2014	18	28/07/2014 18:00	Sunny Intervals	21	14	NE	53	VG	1015	6.26

Table 9: Example of BBC day ahead extracted data

Western Power Distribution (East Midlands) plc
Registered in England and Wales No. 2366923
Registered Office: Avonbank, Feeder Road, Bristol BS2 0TB

Western Power Distribution (West Midlands) plc
Registered in England and Wales No. 3600574
Registered Office: Avonbank, Feeder Road, Bristol BS2 0TB

Western Power Distribution (South West) plc
Registered in England and Wales No. 2366894
Registered Office: Avonbank, Feeder Road, Bristol BS2 0TB

Western Power Distribution (South Wales) plc
Registered in Wales No. 2366985
Registered Office: Avonbank, Feeder Road, Bristol BS2 0TB