Project FALCON

SIM Workstream Final Report

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Contents

Executive Summary

The FALCON Project has delivered a proof of concept (pilot) version of the Scenario Investment Model (SIM) software tool and used it for modelling a number of scenarios in the network trials area in Milton Keynes. As a result of the network modelling activity we have been able to draw a number of preliminary conclusions about network evolution in the town and its surrounding area as well as gauging a number of different strategies for handling network overloads as these occurred in the modelled scenarios and assessing the theoretical implementation of intervention techniques involved in field trials.

The project achieved the following main objectives:

- A derived consolidated database of network definition parameters (the Authorised Network Model) was compiled. This was created in a repeatable format from multiple operational sources and presented to the SIM to allow it to obtain a substantially complete and accurate detailed 11kV distribution network model at the nodal level which was capable of supporting the type of modelling required by the SIM;
- The project identified a number of limitations in the available network data, some of which derived from shortcomings in the sources. Based on this, indications as to future data requirements for the support of smart grid operations were sought and are presented in line with the project learning objectives in this area;
- Detailed results were obtained from real-world network trials covering the same network area and used to inform the SIM models. These were either adjusted to incorporate a series of suggested enhancements into the SIM modelling algorithms in order to improve their accuracy, or else future adjustments were outlined for possible later inclusion in the system;
- The project explored how to handle the representation of costs of various actions and interventions in the SIM and made a number of observations concerning both this process and the nature of the data itself;
- A software engineering approach was derived for implementing the SIM as a network evolutionary modelling tool. There were a number of aspects to this, but the design and implementation of an innovative search space exploration algorithm, the adaptation of an existing Network Modelling Tool for use as a system kernel, execution optimisation and the means whereby complex and extensive results can be represented meaningfully to the users were key aspects with successful outcomes;
- A set of modelling scenarios were identified and supporting data was generated covering load evolution from which the SIM experiments, exploring network response to these scenarios, could then be carried out. These experiments were evaluated and compared to other reference models to draw a number of conclusions;
- A potential strategy for the future development of the SIM has been determined.

The project was successful in these objectives but arrived at the final result somewhat later than expected due to an extended integration phase which therefore required the project to adapt in an agile fashion to these changed circumstances. The design and build was carried out mainly to plan though the series of Rapid Application Development (RAD)

cycles initially intended to incorporate user feedback and enhancements into the system were not carried out. The main result of this was the foreshortening of the final project phase executing the reference Runs. However a number of useful reference RUNs were conducted in time to complete the final report.

In summary, and as described in more detail throughout the rest of this final report document, the success criteria determined at the start of the project have been met:

- **Does it work?** Yes
  - **Functionally.** Runs generated outputs for a series of postulated scenarios from which there are significant conclusions that can be drawn about future operations.
  - **Performance and reliability**. After an extended integration the SIM worked reliably and on an acceptable timeframe given the limited size of the networks under consideration though the application is processor intensive. A future SIM version will require a considered host environment and careful optimisation. The production environment for carrying out Runs required the deployment of multiple, though low cost, host machines allowing experiments to be conducted in parallel. Performance enhancements were seen during development by altering the operation of the A star search and by applying a custom order to technique application. Further opportunities for performance enhancement exist in terms of narrowing down the range of potential technique applications to reflect those most likely to provide value for money. E.g. limiting the options for battery replacement such that there is a limit on the degree of oversizing.
  - **Extensibility** (i.e. ability to process other network areas, need for Authorised Network Model input and associated Load Profiles. Potential for different elements unknown in the initial trials area). The SIM is concluded to be extensible but not without some consideration of the data volumes involved and the processing times. However thought needs to be given to how large an area the tool should be asked to analyse. For local planners the network area is very small (not really extending beyond consideration of a single feeder and certainly within the scope of a single primary substation), however for strategic users it will usually be larger – but how large? An extended dialogue is needed with the strategic users to answer this and other questions once the SIM enters full operational trials prior to any adoption as a business planning tool. The project has also developed a methodology to accurately aggregate modelling results from a number of RUNs each analysing a single primary network into a consistent view of a larger area. The methodology facilitates the analysis of networks of arbitrary size in linear time.
  - **User interaction**
  - Testing has involved the use of the system for 11kV planning and strategic planning. The main issue for the 11kV planner was the difficulty in interpreting the geographic representation of the network which did not provide the same ease of interpretation as a schematic view. Providing a schematic view with IPSA is a possibility, however this would require some additional work to ensure that

technique patches could update the schematic as well as the underlying IPSA model. This is not straightforward as updating the schematic network is currently a manual process relying on drawing office expertise to ensure clarity, rather than the schematic network being automatically generated from the connectivity data using algorithms to optimise the network layout.

From the strategic planner perspective, the network diagram is less of an issue but more use is made of the representations of the simulation results. A python tool to provide a tree view of the results as an HTML file was developed in addition to the results viewer that was originally specified. This has been a far more useful tool to understand the progress of the simulation and suggests both the difficulty of correctly anticipating user requirements for a new process and the value in having the ability to rapidly develop alternatives.

- **Future enhancements and development strategy.** Potential ways forward for the SIM have become clear as a result of the FALCON Project and some work has already begun on developments to support extension of the tool beyond the prototype.

SECTION 1

Introduction

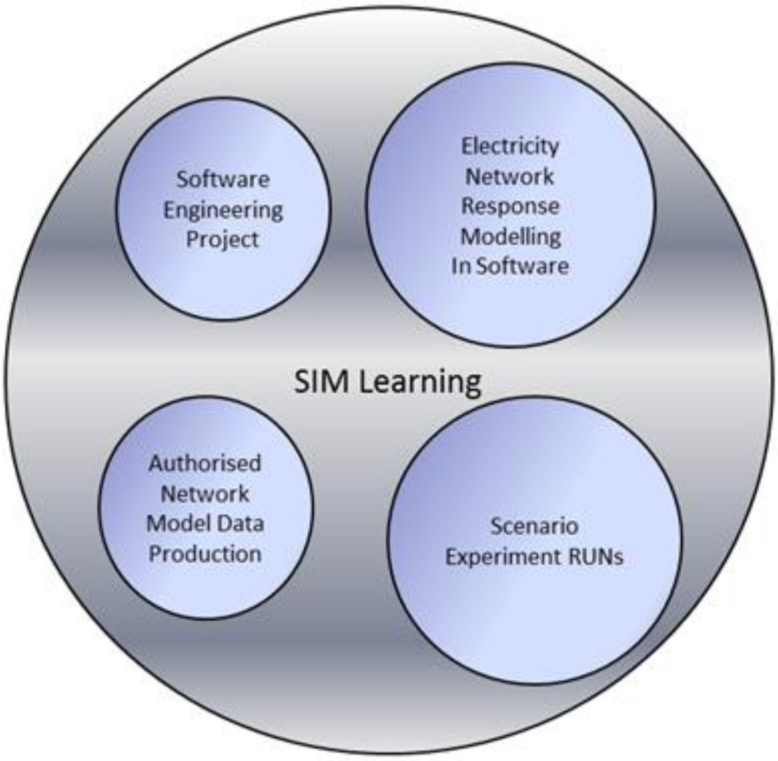
The SIM Workstream (which in the wider sense also includes data preparation and energy model output preparation) set out with a number of high level questions which the project sought to address.

1. Is it possible to improve 11kV planning?
2. Can a single tool support both strategic and business planners?
3. What new data does a DNO need in a low carbon world?
4. What are the algorithms, assumptions, simplifications that have been used and how could these be improved in future releases?
5. How do we manage data from legacy systems and address challenges in migration?

These points will be considered in detail later in the document.

Many other points of learning also emerged on the way to answering these questions and are also presented in this report. The overall learning points from the SIM workstream fall conveniently into four main subject matter areas as illustrated in the figure below, and around which this document is organised.

Figure 1: SIM Learning by Area



Source: FALCON Project

The main areas of this Report are therefore:

1. The implementation of the SIM software system as a technical development project;
2. The specific software implementation technical elements associated with the novel aspects of the SIM in terms of how the system goes about the detailed modelling of the electricity distribution network in the trials/test area;
3. Network data gathering from diverse sources and from these the generation of an Authorised Network Model presenting a complete and self-consistent network model to the SIM, and;
4. The engineering and commercial/planning conclusions which can be drawn from the execution and subsequent analysis of the planned series of SIM Experiment Runs along with an assessment of the efficacy of the SIM as a Network Modelling Tool.

A further key project learning point relates to the FALCON Engineering Trials and how their conclusions were fed back into the SIM. These learning points are covered extensively in the FALCON Trials Final Reports and have in some cases already been assimilated by the FALCON SIM prototype via the mechanism of active technique adjustments.

In the learning areas list above, Points (1) and (2) relate to the development phase of the SIM software system rather than the learning derived by running the tool. These points are subtly different from each other:

- Point (1) offers few opportunities for making novel observations for the wider dissemination audience given that software development and integration is a familiar path, albeit not in a core area of expertise for a DNO such as Western Power Distribution. It will readily be seen that in this case, the key learning to be derived under point (1) is for WPD and its contractors and is largely expected to benefit the organisation (or other DNOs perhaps) in terms of conducting future work of a similar nature. Given this clear indication of scope for learning, we will be making only a few generalised summary conclusions about this area of the SIM development workstream while documenting what was done;
- Point (2) is the main area of interest for the purposes of wider dissemination of learning points in terms of the software related aspects of the SIM workstream developments. The SIM is a new and novel approach to the modelling of electrical distribution networks at the detailed nodal level and provides a means of following the network response and evolution options under a number of different prevailing conditions. Many learning points have emerged from the development of such a modelling capability and these have a very wide scope for interest within the electricity distribution industry. The sort of learning emerging here concerns modelling of engineering intervention techniques, approximations and assumptions which have needed to be made and how we architected the system to achieve its engineering modelling goals, optimised execution times and configured the system search heuristics.

Point (3) concerns the learning generated from the FALCON workstream which compiled the Authorised Network Model database from a diverse range of operational sources. These sources are not explicitly connected to each other and therefore the process of deriving a unified, normalised and accurate data source for the network elements needed as a fundamental input driving the SIM was a key and complex dependency for the success of the SIM overall.

Point (4) concerns the core learning derived by actually using the completed SIM as a distribution network planning/modelling tool operating on a specific pilot trial area of network. As such point 4 clearly covers the main target learning area for a DNO, whereas the other points are essentially collateral material gathered along the way.

The FALCON project has identified an initial series of some 28 strategic "Experiment" Runs which model various postulated scenarios as an initial[1] view of network evolutionary response to a range of prevailing conditions. These scenarios explore the network response to different global demand scenarios and effects such as clustering and different technique availabilities, but also probe the SIM response (specifically accuracy) to a number of parameters such as simulation horizon (timeframe), network scale (size of analysed area) and processing time. The results of using the SIM to model the network in this new way may be used for guiding future investment planning and understanding the limits of the SIM itself as both a short term planning and evaluation tool and as a tool for the development of future network investment and management strategy. This report looks at a number of these initial Runs. These are principally concerned with the projections coming from the main DECC scenarios. The report also looks at the effectiveness of the SIM as an evaluation tool for the 11kV Planner.

1.1 Approach of this Document

To substantiate the project conclusions, the project history and technical findings covering the four main learning areas detailed above are presented in detail in the sections below. Across the SIM workstream overall, this document addresses the following questions which will form the basis of the final critical assessment of the work in the main conclusions and Executive Overview sections:

- What did we set out to learn?
- How did we go about it?
- How successful were we?
- With the benefit of experience what would we have done differently?

The overall document structure is thus:

- Executive Overview
- Introduction Section
- **Scenario Investment Model (SIM) Technical Overview**

Covering Genesis of the SIM, SIM Components and Structure, SIM Techniques, Trials Limitations, SIM Cost Model

[1] Initial in the sense that this is derived from the early "pilot" proof of concept SIM system.

- **Implementation of the SIM Software System**

Covering how the software was built from a software point of view

- **Software Nodal Modelling of Electricity Distribution Network Evolution**

Covering Technique Modelling in SIM, Exploring the Solution Search Space, Trials Feedback Inclusion, Cost Model Implementation, SIM Main Assumptions, Intervention Technique Implementation, SIM Support Tools, Data Issues, Future Enhancements and Development Strategy

- **Authorised Network Model Production**

Covering the datasets and method used to create the SIM's combined network model.

- **SIM RUN Analysis and Conclusions**

Covering the results of some shorter SIM Runs representing 11kV planner usage and Runs extending to 2050 representing a strategic planner's use of the system.

- **Summary of Conclusions**
- **Appendices**

1.2 Scope

This report covers the SIM workstream within project FALCON. Reference is made in a number of places to documents and findings in the related but separate Engineering Trials and Energy modelling workstreams. The Authorised Network Model data extraction, transform and Load Estimation workstream is included within the scope of this report however, as it is intimately connected to the SIM and was completed early in the overall FALCON work programme.

1.3 References and Glossary

The reference document set is presented in a separate document. Acronyms, abbreviations and a project glossary are also held in a separate document called *FALCON Master Glossary of Terms* which is common to all FALCON reports.

1.4 A Note on Terminology

Throughout this document, as elsewhere on the FALCON Project, the term Traditional Reinforcement has been used to mean Conventional Reinforcement. This is for historic reasons.

The term DSM has also been used to mean Demand Side Response (DSR) Load Reduction as distinct from Distributed Generation.

1.5 Acknowledgements

The cover image shows the Bradwell Abbey Bulk Supply Point and FALCON enabled Primary Substation taken during the FALCON Project MEWP Telecommunications Survey in 2012.

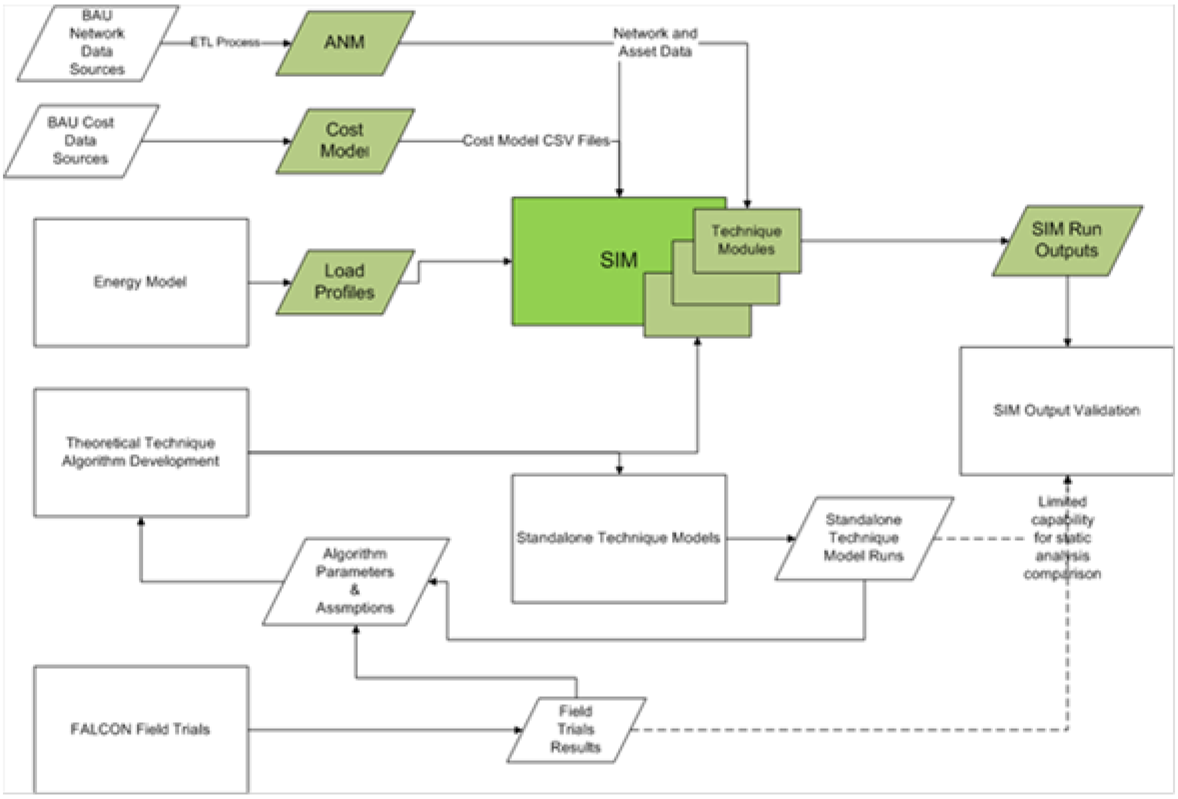
SECTION 2

Scenario Investment Model SIM Technical Overview

The diagram below shows the SIM in the overall FALCON project context. The major workstreams and data elements as well as the linkage between them are illustrated.

At the project outset, the high level objectives identified for the SIM were that it was to be used to find the most cost-effective way to manage an 11kV distribution network over periods of up to (around) 35 years, out to the year 2050, to explore the network response to a range of theoretical demand scenarios and investigate the result of deploying selected intervention techniques to address network overloads.

Figure 2: SIM Context



Source: FALCON Project

It was expected that using the SIM would make it possible to explore possibilities and then select the best approach to managing network constraints arising as load changes (in response to modelled customer behaviour and deployment of emerging technologies) given a range of technical and economic criteria. The project therefore set out to develop a software system and supporting infrastructure that would achieve these objectives.

The SIM identifies network constraints under multiple future network load scenarios and determines the most cost-effective and timely combination of remedial techniques to resolve them. To achieve this, the SIM utilises an enhanced version of the TNEI proprietary IPSA modelling product as its core Network Modelling Tool (NMT) component, but conducts many iterations of analysis for different day types stepping forward through the years requested. The design requires a sufficiently accurate network topology dataset populated with appropriate electrical, thermal and other network component attributes. The actual dataset provided by FALCON for the SIM is termed the Authorised Network Model.

Matching against nodal points in the network are customer loads, these are implemented as Load Profiles, being arrays of load values arranged on a daily basis at 30 minute intervals (so that 48 load points make up a diurnal load profile for a given site and day type). The SIM evaluates the network against the loads on an annual basis, moving through the years specified in the evaluation interval and carrying out each new analysis using these evolving loads. A SIM “year” consists of just eighteen “*characteristic days*” which provide a pragmatic way to handle modelling of the intra-year time dimension as these cover the main types and extremes of load that would be expected to be encountered in a given year. Essentially, each day in a real year can be assigned to one of the 18 characteristic days and by using the number of each representative days in a real year annual metrics can be calculated for items such as losses or network utilisation. The SIM thus performs load flow analysis for the network for the 48 half-hourly periods during the day for different days of the week and different seasons of the year. Predicted load patterns generated from the Energy Model and imported into the SIM extend as far as 2050. For more information on the Energy Model and the scenarios please refer to the Scenarios Consultation Document and FALCON Load Estimation Final Report.

When power flow analysis within the SIM detects a voltage or thermal issue, the SIM will select from the supported remedial 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, per use and operating costs, network performance, losses and disruption to customers. While some aspects of the various solutions can be assessed at the time an issue is reported, the longer term value for money of the options is determined by how they contribute to the overall performance of the network over a number of years. So for example a solution that is initially expensive may be value for money if this results in many years of issue-free operation. Therefore the SIM does not use a “merit order” approach to resolving network issues i.e. applying the technique which is expected to provide best value for money based on initial costs, but rather the SIM allows for the long term value to become apparent by allowing the simulation to branch. This creates a large number of potential options for the evolution of the network which requires a search mechanism to guide the search through the solution space. The guided search mechanism for the SIM is a modified version of the A * Search (pronounced A star) which incorporates a learning algorithm to provide feedback from the analysis carried out to refine the view of expected costs in a particular year. The A* search also requires a costing model which provides an accurate means of assigning costs to the interventions carried out, as well as including the costs of regulator imposed penalties resulting from network failure conditions (CI/CML etc). These costs and penalties therefore feature in the analysis and the choices made, and are reported on an annual basis in the SIM Results.

The SIM therefore evaluates the impact on the network of a sequence of chosen experimental scenarios and looks at alternative paths to and consequences of resolution. This can help direct strategic planning of future networks given a range of options about how the future will unfold out to a timeline of around 2050. The SIM also enhances the business as usual planning process by providing a medium term view to 11kV planners of the impacts of their design choices.

For the purposes of the FALCON SIM system development (including the trials that inform it) it was necessary to choose a set of initial remedial techniques, and these were built into the development. The actual techniques that were chosen from among those candidates that were available at the time are described in Section 4.7 of this document.

2.1 Genesis of the SIM

The SIM concept took shape at the time of the FALCON Proposal to OFGEM and was seen as the tool by which the smart solutions could be evaluated against traditional reinforcement at the 11kV voltage level. Right from the earliest stage it was anticipated that there would be some scenario based analysis so that the impact of different assumptions could be assessed. The concept of the SIM was influenced by other modelling being carried out in work stream 3 of the Smart Grid Forum where the predecessor to the Transform model was being used to answer broad brush questions such as whether smart technologies were likely to be cheaper than traditional reinforcement in the long term. The workstream 3 model would also investigate whether there was an economic argument for wide scale investment in smart enablers i.e. a “top down” investment approach rather than implementing smart technologies incrementally in different areas as need arose.

2.1.1 Core Functions of the SIM

The key distinguishing factor for the SIM was to be the way in which the solutions would be evaluated, with techniques being applied and simulated with reference to a nodal model of a real network, rather than assessing networks in terms of percentage headroom for representative network types. The SIM is seen therefore as a detailed bottom up model based on microscopic level analysis while other existing models can be characterised as top down macroscopic simulations based on summary views of the network. These two very different views ought to be complementary and there may even be expected to be some overlap in the middle ground when applied to the same network. However it can be hard to find representative networks to check this aspect, and using average networks could potentially underestimate the levels of investment required. Also, networks that are more stressed than average networks can be lost in the averaging process and clustering was seen to be one of the key sensitivities for the Transform Model.

The target functionality of the SIM was confirmed at the procurement stage when the distinction between the Network Modelling Tool, as the engineering heart of the SIM (performing the power flow analysis to determine network issues), and the SIM Harness (managing the branching simulation and providing the data to the NMT), became clearer.

Other functions to be included in the SIM derived from the learning that was expected to be achieved and the level of information that would need to be presented to the users concerning how results had been obtained. For example, to simulate the network impact over a long time frame meant that the SIM was required to handle multiple years' worth of data, and that it also be capable of reporting on a range of parameters and metrics, and the search for solutions be guided by costs (which could also be adjusted).

Some of the ancillary support functions originally allocated to the SIM itself also ended up being redefined as functions to be performed externally in cases where the functionality required was not in the final analysis found to be a good fit for either the SIM Harness or the NMT. So, for instance, the production of load estimates was separated out, as was the mechanism to reflect different economic assumptions, which eventually became known as the *cost model*. Similarly the SIM was originally foreseen to be the repository of all the results of the various simulations and therefore it was considered that the SIM would also perform much of the post simulation analytics to determine which features of a network or scenario would result in a particular technique being the preferred option. Such refinements largely dropped out during the design phases. An external results database inspection tool was also added to aid integration testing and to support the *Experiment Run* phase of the FALCON project.

2.2 Choice of NMT

Five Network Modelling Tool vendors were invited to tender to provide the NMT for FALCON. Many of these were already operating in the UK and were in use by various DNOs, while one was in use in Europe but not yet in the UK. Three of these vendors provided written responses and presentations to allow their proposals to be assessed.

The criteria for assessment included consideration of the following:

- Functionality that was already demonstrable in the product;
- Risks around additional functionality development and delivery and willingness to participate in such a development programme;
- Ease for interfacing with the product;
- Performance and speed of operation;
- User perception of the visualisations and user interfaces;
- Any spin-off benefits that could be anticipated;
- Price.

Network Modelling Tools vary a little in their accuracy due to the differences in their assumptions. For example, a modelling tool that assumes that load is balanced equally between three phases will be able to model the network in a simplified, faster way than a model which does not assume balanced phases. While the unbalanced model has the potential to be more accurate, this is only the case if the supporting data for the individual phases can be provided accurately. As the Network Modelling Tools are generally applying Kirchoff and Ohm's laws which are known to be accurate, the biggest factor affecting precision in the results will be the accuracy of the data within the nodal model that specifies cable types, cable lengths, connectivity etc. It is very difficult to assess the quality of this data, partly because the data is constantly being updated, but also because some elements such as underground cable types and lengths are hard to validate visually.

At the end of the process TNEI were chosen for their IPSA tool which became the SIM NMT kernel. This followed careful evaluation of a number of the above criteria, with IPSA finally emerging as the best option because the tool was seen as being adaptable. TNEI had already planned a number of enhancements to IPSA, such as allowing for sequential half hourly analysis, which aligned well with the requirements of FALCON, and their future product enhancement strategy could also benefit from the inclusion of a number of elements of FALCON functionality.

2.3 SIM Components and Structure

The overall design of the SIM was presented at the end of the design phase and at High Level in the Architectural Design Document where each of the subsystems described later in outline was allocated a chapter. The ADD was produced and approved before any code was written in accordance with standard software development practice, itself having been further developed from a well structured “SIM Design Blueprint” document (document available upon request) where the framework of the design had already been laid down. The Blueprint had been written very early on in the project lifecycle and received review by both OFGEM and several third parties including DNO’s such that the final version of this document included the agreed review comments.

The SIM as designed and implemented has four main component elements:

- SIM kernel engine, the Network Modelling Tool or NMT, based on an enhanced version of the commercial power flow analysis tool IPSA from TNEI;
- A SIM Harness (SIMH) which encapsulates the NMT and exposes the kernel functionality to the overall SIM tool and where necessary to the user, manages data input and output and also drives the search through the solution space. Essentially the SIMH turns the NMT into an enhanced modelling solution that has been likened, in a useful analogy, to the provision of a dynamic network movie (SIM) rather than a static snapshot/photograph (NMT). Components include:
  - Worker machine, a VM that actually calls the ipsa_wrapper and performs evaluations;
  - MCP machine, manages high-level experiment control functionality (experiment start/pause/delete, etc);
  - GUI machine, while not actually a VM, this is code that is Run on the client computer that starts up a web server providing UI services supporting user interaction with the SIM;
- A Wrapper layer supplying utility APIs which interfaces between the NMT kernel and the SIM Harness;
- Support infrastructure including host environment and data elements.

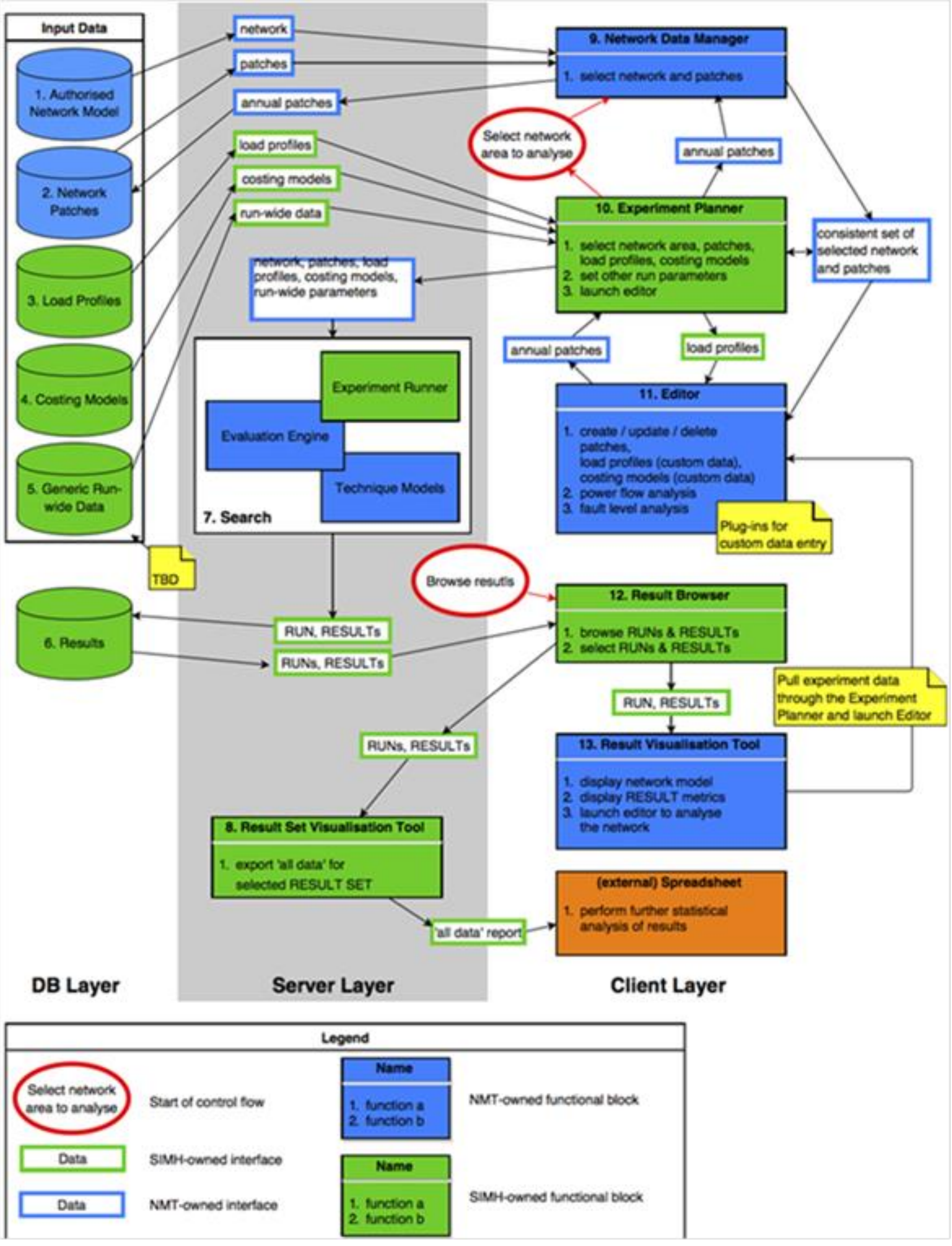
- Libmsg module, which handles data transfer between SIM harness machines;
- Libdata module, which sits on top of the libmsg, and provides facilities to access database data for all SIM Harness machines except the "orm" machine (that machine actually serves as data server for the libdata module);
- Host machine, this is code nominally Running on the server that hosts VMs. It provides facilities to replace VMs with newer VMs with an updated code base and manages the pool of Running VMs (e.g. MCP machine can request more 'worker' instances to speed up execution);
- Build machine, this is a VM which generates CD disk images (ISOs) to be used to spawn a next generation of VMs.

A number of software subsystems and main data elements comprise the overall software suite which was functionally decomposed in the usual software engineering fashion to increasing levels of complexity during the high level design phase of the project.

The SIM subsystems/datastores and their main functions are:

- Host environment (platform, messaging system, virtual machine management);
- Input data stores (SIMH);
  - Authorised Network Model (the virtual model of the 11kV distribution network);
  - Network patches (enhancements to the base network to accommodate planned or possible change);
  - Load profiles originating from the Energy Model (representing customer load at each modelled node location);
  - Costing models (cost elements associated with the technique application);
  - Generic Run-wide data (various supporting data items);
  - Results store (SIMH, outputs from the SIM experiments);
- Search subsystem (A closely coupled joint function between the NMT and SIMH Elements which explores the solution space and finds resolved network states);
- Experiment Runner (SIMH) and Evaluation Engine/Technique Models (NMT));
- Result set visualisation tool (SIMH);
- Network Data Manager (NDM, an NMT component);
- Experiment planner (SIMH used for setting up the parameters defining an experiment and managing its execution);
- Editor function (NMT, used for viewing and editing a network);
- Result Browser (SIMH);
- Result Visualisation Tool (NMT).

Figure 3: SIM High Level Architecture



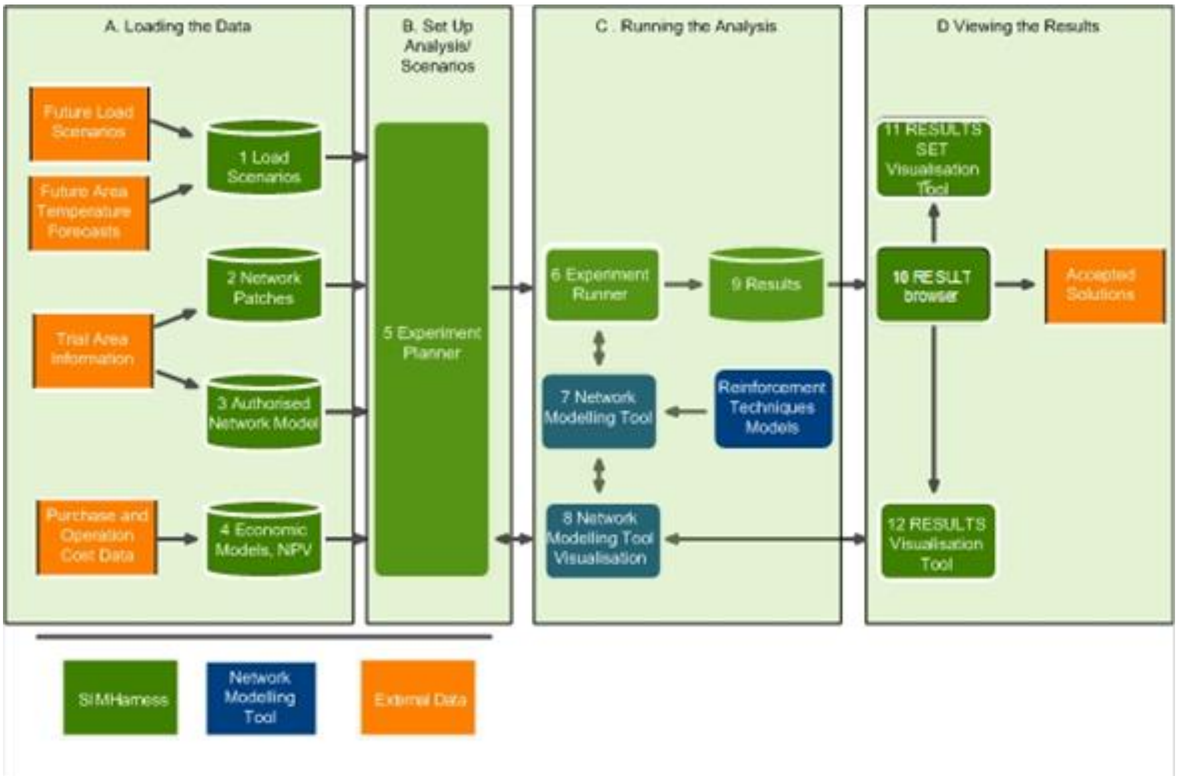
Source: SIM Architectural Design Document

In carrying out the next level of design expansion to the low (detailed) Level, a new series of Detailed Design Documents (DDDs) and WIKI specifications were produced (where necessary) with a new DDD document corresponding to each main chapter of the ADD. Given the completeness of the ADD, these DDD documents were prepared in tandem with the code production, rather than this being done before any code was produced. Some of the documentation is covered not by project specific documentation but by pre-existing TNEI product material associated with the IPSA product around which the SIM is organised.

The above approach was very successful, the functional decomposition was self-evident, essentially followed a structure naturally imposed by control flow, was logical and corresponded well with the SIM function as well as accommodating the various constraints imposed by using an extant kernel system for the NMT kernel.

2.4 SIM Processing Flow and Control

Figure 4: SIM Subsystems and Control Flow



Source: FALCON Project SIM Blueprint

Overall, the SIM supports the following generic workflow:

- The Authorised Network Model is imported from an external source;
- The Load Profiles are generated by the energy model and imported into the SIM;

- The Engineer may create network patches, adjusted load profiles and costing models needed for their experiment if they do not already exist or require adjustment;
- The Engineer defines the inputs to one or more Runs of the SIM using the *Experiment Planne*r. For each Run the SIM needs to know the network area and patches (if any) to be applied. The Engineer is expected to define a series of Runs (a Run Set) that will provide the data necessary to answer the questions they are seeking to address. The SIM does not, however, guide the Engineer in this process;
- The SIM processes the Run Set defined by the Engineer;
- All Results are saved to a result store;
- The Engineer may select from the store of results, the Runs and Results to use for inspection and reporting;
- The Engineer may perform either an in-depth inspection of a single Result or export one or several Results into an external spreadsheet program for analysis. It is also possible for expert users to directly access the SIM results store/database to perform complex queries on the Run data. The latter mode is used particularly by the pilot SIM development project.

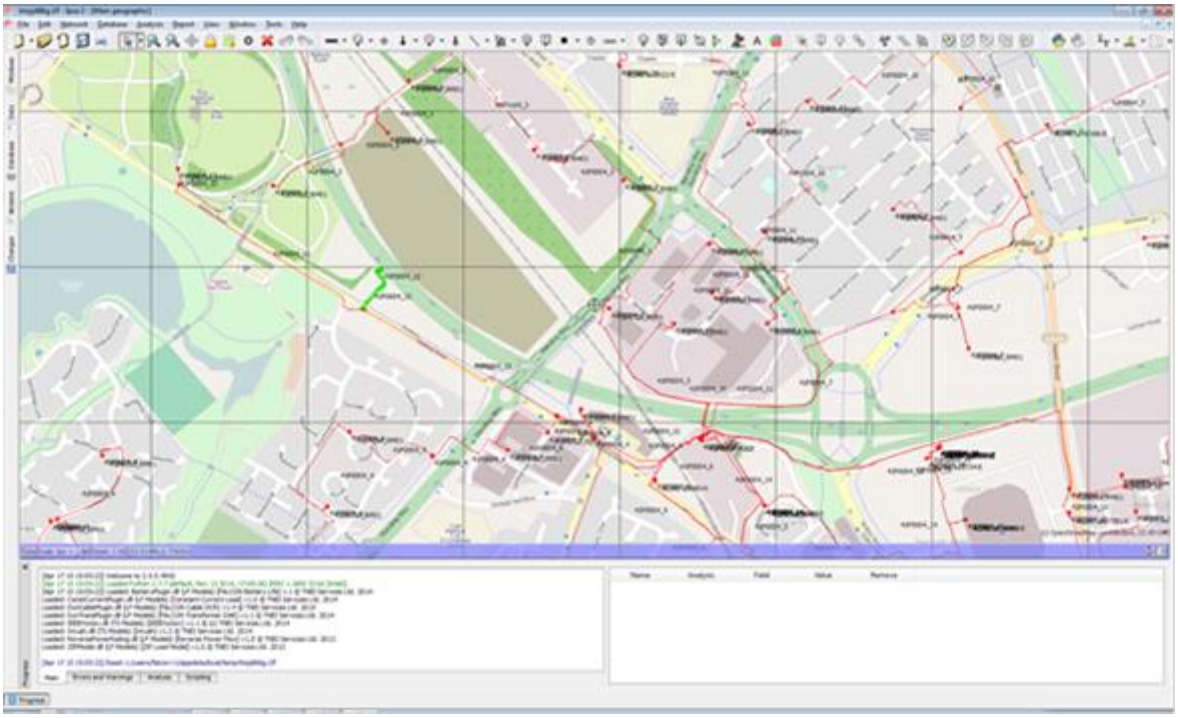
2.5 SIM Inputs and Outputs

The SIM external data sources are illustrated above in Figure 4 where the main data units are identified. There are a variety of data formats used (including CSV files and database formats) for the import into the SIM of network, cost and load data.

Most of the user interaction with the SIM is achieved via screen input and output. The main SIM control screens, which form part of the SIM harness, are implemented in a captive browser (i.e. in web format) while the IPSA NMT GUI components (which deal in the main with the representation and rendering of the network elements) and which were pre-existing, are implemented using the Digia QT widget library. The original intention of the SIM workstream design process had been to ensure, largely through the use of the same Widget library, a consistent appearance with coordinated use of colours, naming conventions, behaviours, layout and general appearance thus giving a harmonised interface. During the early project implementation, however, a decision was taken to revise the SIMH approach to become browser based as this offered more flexibility in the design as well as aligning to a strategic wish within TNEI do a similar future product enhancement for the IPSA user interface components. Full harmonisation would therefore become a next phase SIM objective rather than achieving this early using a non-strategic basis for graphics representation.

Some representative SIM operating screens are shown below.

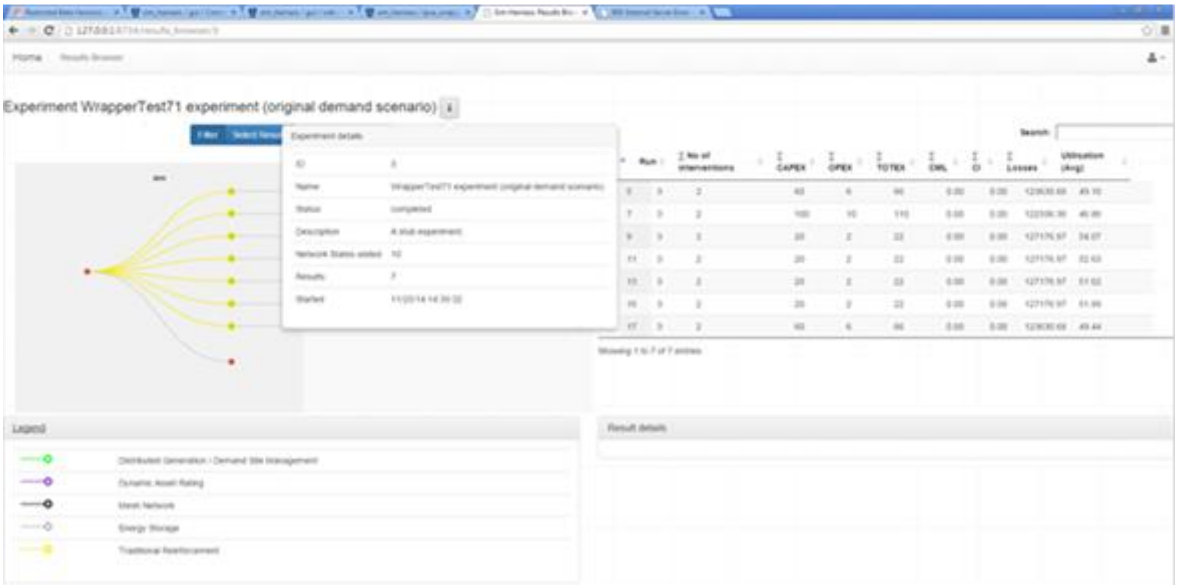
Figure 5: SIM Network Data Manager - Network Selection



Source: SIM Network Editor

The above figure illustrates the initial network selection function which is an IPSA format display. Once the SIM has Result for a Run, the results can be displayed and inspected in the result viewer shown below. The same window also allows the progress of an executing experiment to be monitored.

Figure 6: SIM Result Viewer



Source: SIM GUI

The SIM can also export results to a report file in a format compatible with MS Excel (a common downstream analysis tool), however the main SIM results are written to its internal database. In addition to the SIM “on-board” functionality for viewing results, offline database inspection tools have also been developed to support the conduct of direct and in-depth analysis by data mining the results database.

2.6 SIM Users

The original SIM concept envisaged three distinct user types for the production BAU SIM.

- 11kV Planners who would use the SIM to plan work on a specific very localised area of the network to perform short-term (up to 5 year forward) analysis of the effects of change/model evolution of the network in that area;
- Strategic Planners who would want an overall view of large areas of networks potentially over much more extended intervals;
- Policy users who would be interested in understanding the implications of changing the way the 11kV network is managed.

Additional classes of user made use of the SIM during the development i.e. Expert Users and Researchers. These users work together to develop, test and validate and finally to execute the main SIM experiment Runs for presentation later in this document or elsewhere. The expert users of the pilot SIM mainly interacted with the SIM outputs using direct database access including the use of a bespoke database access tool.

2.6.1 User Engagement

It was a project priority to set up a *User Group* very early in the overall design phase of the project with a view to two way communication with these important project stakeholders. The intention was that the User Group forum would inform the prospective users of what the SIM was as well as keeping them up-to-date with the status of the ongoing development, and regularly gather valuable inputs via the medium of feedback on Newsletters and from SIM briefings. Users were drawn from across WPD both in terms of geography and role with the biggest grouping being the 11kV Planners.

The initial meetings were concerned with outlining the main SIM design and operating concept. Later meetings presented SIM elements as they became available and sought feedback from the users on matters such as performance (Run duration was a key point of interest), symbology, screen layout and assumed knowledge. One problem for the User Group was the length of time between seeking views and having a demonstrable version of the software. As well as it being difficult to maintain momentum, there were staff changes that affected the user group. Some user resistance was noted which may reflect the degree of change implied by such advanced automation tools as the SIM to current working practices in the industry.

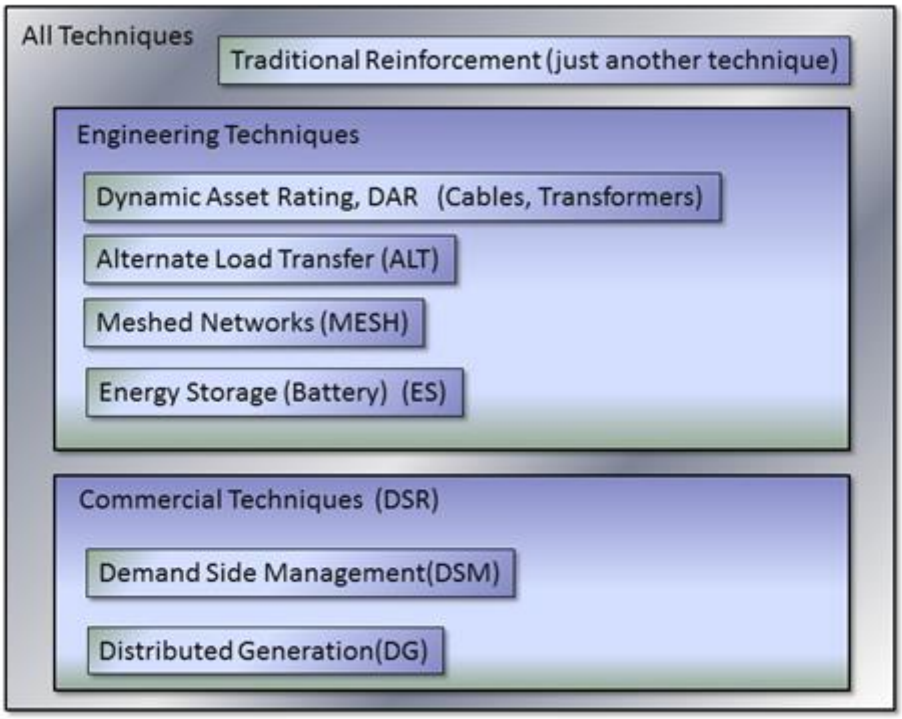
2.7 SIM Intervention Techniques

Techniques are interventions applied to the real world network to fix a known network constraint. The techniques chosen to be trialled in the field by the FALCON project and also modelled and deployed by the SIM were those that were considered to have a high chance of being practicable for the 11kV network and included both active and dynamic elements.

The diagram below identifies and illustrates the techniques used by the SIM and their categorisation. It is also seen that the SIM treats *traditional reinforcement* as if it were just another technique, even though this is the remedial "technique" of choice in the current operating model for most DNOs. This pragmatic approach to deploying intervention methods allowed for a simplified and generic approach to technique implementation by the SIM. This is described in detail in Section 4.7 below.

With the FALCON field trials deploying the same techniques (other than traditional reinforcement) it was thus possible for the project to inform the SIM implementation of the modelling of these. This document includes sections on this "feedback" but also identifies the limitations of the trials in this respect in the following section.

Figure 7: The FALCON Techniques



Source: FALCON Project

2.8 Trials Limitations

The actual FALCON real-world field trials and the SIM network evolutionary modelling were targeted at performing very different tasks and that these two activities really only come together where the trials outcomes help to make the SIM modelling more accurate through a process of feedback. Other points of difference are:

- Trials were not investigating N-1 configurations and there are no actual constraints on the network to which the trials are deployed;
- The locations of all trials deployments were pre-determined and fixed once installed. The SIM, on the other hand, seeks in the first instance to determine which technique should be deployed in the event of a constraint and where to deploy it over a range of combinations of solutions. Thus the SIM activity of optimally locating an intervention technique in response to a constraint arising is never actually reproduced in the trials. Numerous factors were included in the decision making process for determining where to place the field trials and many of these factors could not be known to the SIM in its current form (for example – for battery locations, critical factors in placement included a view as to how many customers might be affected by equipment noise, the nature of which was uncertain before trials commenced and the potential of the substation location to be extended to site a new battery unit – again information that is not currently held by the Authorised Network Model);
- The trials would evaluate a set of procedures and activities covering the new commercial and engineering techniques. As these techniques are relatively new to DNOs and have variations in the way in which they can be applied, it was not immediately clear which would carry on into actual BAU operations and thus what elements should in due course be included in the SIM. In part this is what the FALCON project was intended to explore under its main objectives. However we note that the evaluation of the trials and implications for BAU options for network management is a process which may take several years – so only certain options were adopted in the SIM technique implementations for the Pilot Proof-of-concept;
- The trials were covering only a subset of the nodes in the overall SIM modelled network. FALCON had some 200 locations (including nine primaries and some 190 secondary substations) fitted with WiMAX communications capability along with intervention and/or monitoring equipment. In contrast the Authorised Network Model covering the FALCON core area around the six key primaries included 579 secondary substations in the core area and a further 1155 substations located in the "periphery" on adjacent feeders (this periphery being needed to ensure that where feeders outside the core area were used to backfeed networks under N-1 analysis, that the uptake of low carbon technologies was reflected consistently).

2.9 SIM Cost Model

The costing of SIM interventions (these are the network investment when summed) is computed within the SIM harness (SIMH) based on the following inputs:

- The number of assets of each type installed / replaced / upgraded during a RUN and which is included in each patch, being advised by the NMT;
- The "*cost*" per unit of installing/ replacing / upgrading each asset. The values are included in the cost model and are imported into the SIM during initialisation (based on WPD originating values from BAU and other similar sources).

For most of the techniques the elements included in the automatically generated patch is relatively straightforward to calculate. However for the reinforcement technique, and manually designed patches, matters are a little more complicated as there are a number of different asset options and it is not always possible to cater for all possibilities.

The cost drivers reflect three main elements of cost, being: initial (CAPEX) cost, the ongoing (OPEX) costs for support and maintenance, and the per-use cost. As a further dimension there are a number of regulatory reporting "bucket areas" into which costs are apportioned, though it should be added that the allocation of component costs to these different allocations is in most cases an accounting rather than a strictly technical consideration and the SIM works in any case on the overall total cost in steering the solution search. Allocation of costs to buckets is primarily a presentational matter useful to the business when looking at how elemental costs of the interventions are represented.

2.9.1 Network State Metrics

A Network State can be thought of as a node within the branching simulation and reflects a unique instance of the network reflecting a unique combination of base network, patches that have been applied and load data values. A new network state is created when a new patch is applied or when a network state progresses to a new year (and hence new load values).

In addition to the elemental costs for each patch, at the higher level there are also Network State Metrics which are an attribute of each generated Network State. There are a number of these metrics that need to be calculated by the SIM in operation. These metrics are calculated in order to

1. Allow the calculation of the cost metric to direct the A* search;
2. Provide useful information to help a Planning Engineer differentiate between different Results that have similar cost metric values;
3. Support reporting requirements for other SIM users than the Planning Engineer.

In general, if an item is of interest to a Planning Engineer and might be used to support decision making, then it is likely to be included as part of the cost metric. Therefore it is expected that there is a large degree of overlap between items 1 and 2.

Any of the Result Metrics calculated within the SIM could potentially be used as columns in the Results Browser. Therefore users could have some flexibility to choose columns that reflected the data they preferred to see. Column choice was not implemented in the prototype version but could be supported in future developments.

Most of the Result Metrics are aggregated from the corresponding network state metrics. In turn, each network state contains zero or more patches with metrics that aggregate into network state metrics. Therefore, Result Metrics will have two different sources of calculation.

1. Network State Metrics. These are calculated by considering the network as a whole. i.e. CMLs, CIs, Losses and Utilisation.
2. Patch Related Metrics. These relate to the patches applied to the network e.g. installation costs, operational costs, installation man hours etc.

The metrics that are calculated with reference to the whole of the network are

- CMLs;
- Cis;
- Losses;
- Average Network Utilisation;
- Average of Maximum Network Utilisation.

Losses, utilisation and fault levels are calculated on per-feeder basis.

Network Continuity

The network state metrics can only form useful comparators if the network evaluated is consistent. In GROND (another Network Modelling Tool used by DNOs), network analysis of CMLs, CIs and losses would be carried out on a per feeder basis and in the situation where a feeder is split into two, or several feeders are meshed together could result in unreasonable comparisons. This was initially considered to be a potential problem for the SIM, however the way in which the SIM works is different in that the network selected for analysis would typically involve all the feeders that would be considered as options for meshing and all the feeders that would be used as alternative feeds under fault conditions. Therefore in Running the SIM no additional feeders would be added to the network, nor would split feeders disappear from the assessment.

Calculation of CMLs and CIs

Customer Minutes Lost (CMLs) and Customer Interruptions (CIs) are metrics that represent the reliability and availability of a distribution network. They are used in the UK for reporting network performance to Ofgem and have the same purpose as the international standard metrics SAIDI and SAIFI. These values are normalised to take into account the differences in scale between distribution networks and thus CMLs for a DNO are expressed as the total customer minutes lost by that network divided by the total number of customers. CIs are normalised by the total number of customers/100.

This calculation is similar to that performed by GROND. Fault rates for overhead lines and underground cables are far higher than those of switchgear or transformers and so, as a simplifying assumption, only faults on lines and cables are considered.

Thus an assessment of CIs and CMLs can be gained by considering every section of line / cable of the network in turn and assessing;

1. What is the likelihood of fault?
2. How many customers would be interrupted by the relevant protective device(-s)?
3. How quickly can the customers that have been disconnected be restored?

Likelihood of Fault

This will be dictated by whether the conductor is overhead or underground and will vary according to the nature of its construction. E.g. small section overhead conductor will have a higher fault rate than larger conductors.

Fault rates are expressed in terms of expected faults / 100km per annum. These values are calculated annually from data submitted from all the DNOs under NaFIRS. Fault rates for use in the SIM should either reflect the WPD average rates, or where possible the fault rates within the East Midlands DNO area.

Faults can be generally categorised as;

1. Permanent faults, where a part of the network has been damaged and requires repair.
2. Transient faults, where a momentary event like windborne debris connecting across phases of an overhead line triggers a disconnection of the network followed by successful reclosing with no customers off supply for more than three minutes.
3. No damage faults, where a transient fault has caused protective devices to “lock out” causing interruptions of longer than three minutes, but where the network is restored without repair.

To simplify the calculation it was assumed that short interruptions were unlikely to be incentivised or penalised by Ofgem. Therefore transient faults, which only cause short interruptions do not need to be considered.

Similarly, calculation is simplified by using the same calculation methodology for damage and no damage fault and by averaging the fault rates, repair and restoration times across all faults that result in any interruptions over three minutes.

The additional sophistication to calculate CIs and CMLs more accurately could be added at a later date if there were a business justification, however for the FALCON Pilot SIM the simplified form is adopted so as to give a better balance between cost, speed of development and accuracy.

A network is divided into protection zones according to the location of protective devices on the network. These include items such as fuses, intelligent fuses, overhead line reclosers and circuit breakers. Typically for a radial network when a fault occurs the first upstream protective device will operate to isolate the faulty section of network downstream. For meshed networks with unit protection then two protective devices may operate together to ensure that a faulty section of network is isolated from the healthy section of network.

Once the protective devices that would operate are identified it is possible to calculate the number of customers initially affected by the fault. (Note - any customers restored within 3 minutes would then be subtracted from this total, as their interruption would be classed as a short interruption.)

Restoration Time

The network that has been disconnected by the operation of protective devices may include several switching points that can be used to further isolate the healthy network from that which is faulty.

It may be possible to isolate the faulted section of network and restore the healthy sections of network either from the original source or by closing a normal open point. Other sections of network that are healthy, but have no alternative infeed would have to remain de-energised until the fault was repaired. Thus as well as being divided into protection zones the network can be divided into switching zones, i.e. the smallest sections of network that can be isolated by switching. The way in which the network can be restored will depend on the topology and assumptions about whether assets are switchable. While in reality it may be possible to isolate sections of network by disconnecting bows or using live line taps, for simplicity only assets that are normally used as switches should be considered switchable for this analysis. This is consistent with the decision not to include Live Line Taps within the Authorised Network Model.

In reality the restoration process involves both locating the faulty section and restoring healthy sections of network. Fault Passage Indicators would speed up this process, however the additional complexity required to include this level of detail outweighs the benefits in terms of CML accuracy and therefore Fault Passage Indicators have not been included in the Authorised Network Model. Neither do we expect the CML calculation algorithm to differentiate between sites that are easy to access for switching or those that would take longer to reach nor take a view on how fault repair times might be affected by the particular aspects of a fault location.

The speed at which customers will be restored will reflect whether the switching required can be carried out

1. automatically via remote control which does not require control engineer involvement (very likely to be completed in under three minutes);
2. via remote control but requiring the control engineer to initiate switching actions (may or may not be completed in under three minutes);
3. manually without requiring repairs, which will be dictated by the speed at which engineers can typically reach site;

4. manually after repairs are completed which will be dictated by the time repairs take. This will in turn depend on the nature of the network with underground cable faults taking longer than overhead line faults to repair.

The Authorised Network Model includes details of which switching points are telecontrolled, but does not identify telecontrolled switches covered by automation schemes.

Losses

Losses are calculated from power flow analysis based on an understanding of the current flowing. The calculation of losses on the network would include losses associated with lines and cables and losses on distribution transformers. The Authorised Network Model does not have data for distribution transformer losses so assumed values have been used.

The Authorised Network Model has the Copper / Iron loss data for primary transformer losses to be calculated. However the changes are expected to be small and to mirror the changes to losses seen on the HV conductors / transformers. It appears that this additional calculation is unlikely to provide information that would help reporting, or distinguishing between alternative solutions and so would not be necessary.

The losses calculation can provide values for

- KW losses – the resistive I^2R component
- KVar Losses – the reactive iron losses
- KVA total losses – the combination of the two

The following is reported by the NMT per feeder:

- Annual Percentage losses;
- Annual kwh losses;
- Cable Av Utilisation;
- Cable Highest Utilisation;
- Fault levels;
- Fault level constraints;
- Ohl Av Utilisation;
- Ohl Highest Utilisation;
- Tx Av Utilisation;
- Tx Highest Utilisation.

The items below are reported per network

- CI;
- CI total;
- CML;
- CML total;
- Profile path;
- Num Customers.

The user group suggested that the two components should be reported for losses to allow for future flexibility in how these are costed and better understanding of how losses are composed.

Losses are reported in terms of;

1. Total annual losses as KWh - which allows for the actual cost of purchasing that energy to be estimated.
2. Average Percentage losses, which compares the total annual losses to the total energy delivered to the network. Ofgem incentives are more likely to be expressed as a percentage target.

Aggregating Half-hourly Values to Daily and Annual Values

The calculation of losses reflects changes in loads that occur in each half hour and also the impact of ALT , DG and DSR which would further alter network loads and hence losses. Losses are therefore calculated for each half hour and aggregated to daily values. Daily values can be aggregated to annual values by creating a weighted average of day types.

For the calculation of CMLs and CIs the reconfiguration of the network is important as this could affect the number of customers initially affected by a fault. The half hourly variations in load don't affect the CMLs and CIs unless they prevent a backfeed from being used for restoration because this would result in an overload of the network in question. In practice, overload in backfed circuits can often be offloaded with further switching. Ensuring the network is N-1 compliant will mean that we can assume the network can be backfed and so CML/CIs only need to be calculated for each different network configuration that might be experienced in a year rather than for each half hour.

Weighted averages are used to aggregate the values for each network configuration to an annual value. If (e.g.) an ALT scheme results in different Running arrangements being used at different periods of the day, CML/CIs for each arrangement are pro-ratad in proportion to the numbers of half-hourly intervals for which each is in force.

Average Network Utilisation

Network utilisation is an indicator of the degree to which the capacity of a network is being used.

Smart techniques are expected to increase network utilisation. A very high value might indicate that the network may have limited ability to accept new load or that it may be hard to reconfigure the network under maintenance or fault conditions. A very low value might indicate poor value for money for customers that have funded a little used asset. DNOs report Load Indices to Ofgem as a comparative measure of network utilisation however those metrics are more applicable to higher voltages so are not calculated in the same way here.

Static ratings are used for calculation of utilisation therefore it may be possible to achieve values over 100%. The static rating used reflects the seasonal rating. Utilisation is calculated for overhead lines and cables as the current divided by the current rating for each half hourly period.

As transformer ratings are given in kVA then the utilisation of a transformer is the power for each half hour divided by the transformer rating kVA. The half hourly values are combined to create an average over the year.

The utilisation factors for the various parts of a network are then combined in a way that reflects the relative scale of each component. The suggested scale factors to be used are line length and cross section for cables and overhead line and kVA rating for transformers. Thus a high utilisation factor for a long length of larger cable is given more emphasis than would be the case for the same utilisation factor applied to a smaller or shorter cable. The scale elements therefore put more emphasis on assets that would cost more to upgrade. Switchgear is less likely to be upgraded to a higher rating and therefore switchgear is not included in the utilisation metric.

Initially it was planned to combine all the scaled values together into one metric, but following consultation with the user group it was decided to multiply the average utilisation by the line length or transformer rating but then create three separate totals for the scaled values for overhead lines, underground cables and transformers.

Average of Maximum Network Utilisation

This version of the utilisation metric considers only the worst utilisation factor of each network element during the year, rather than the average value of utilisation over a year. The worst values for different network elements will occur at different times but this is acceptable because the metric aims to give a measure of headroom. The worst percentage utilisation values for each cable section or transformer are then combined using the scaling factors of line length and KVA rating as for Average Network Utilisation. This produces three separate values for overhead lines, underground cables and transformers. Once again, the metric value is not intended to be interpreted in itself, but used for comparison over time and between alternatives.

SECTION 3

Implementation of the SIM Software System

As noted previously, this area offers few opportunities for making novel observations for the wider dissemination audience given that software development and integration is an extremely common activity governed by a number of widely accepted methodologies and practices. It would be true to say that as an industry wide activity, the key learning points associated with software management, development, test, integration and support have been extracted, considered and documented to the point of this now being a very mature and well understood area to which very little of any additional value may be added by a standard software development like the SIM.

What learning this area is able to contribute to the project output then, is likely to be limited to lessons for WPD itself (and the associated FALCON contractors) when doing such work in the future, as well as such lessons potentially being beneficial to other DNOs considering similar activities.

The section below describes the approach taken, the solution that was derived and summarises the issues and successes that resulted.

3.1 Background

To understand the development it is necessary to understand how the project went about the SIM implementation, both from a project workstream organisation point of view and then technically. This section provides such a background understanding and then asks how successful we were and what we would consider doing differently should a similar development ever be repeated.

While the SIM forms a major, if not key, central component of the FALCON Project, it is also the case that software design, development, integration, test and operational support are not key DNO capabilities. Having developed an early project deliverable containing a “Blueprint” for the SIM which encapsulated the system requirements, key use cases and some elements of design, it was determined that the role of WPD SIM Project Manager be outsourced to contracting IT Integration experts and existing FALCON Partner organisation Logica (now CGI). This Project Manager would then face-off to two main SIM implementation subcontractor Project Managers working for the two main supplier organisations: Cranfield University IVHM Centre and Manchester based TNEI.

The latter organisation was charged with providing the central kernel component of the SIM, the Network Management Tool (NMT) based on TNEI’s mature product IPSA. IVHM were responsible for the ownership of the overall SIM technical development and specifically the SIM Harness elements (SIMH) which expose the SIM functionality to the user through the operation of the captive NMT.

WPD set up the commercial arrangements separately, managing both TNEI and IVHM as peer organisations supplying in to the FALCON Project. The CGI Project Manager was also engaged as an embedded contractor inside the WPD project FALCON organisation. Technical direction for the SIM, electrical engineering expertise, user group members and continuity from the proposal stage was provided by WPD staff.

The WPD SIM Project Manager (CGI Personnel) commenced working on the project at the completion of the SIM Blueprint stage in October 2012. At this point the System Requirements were already being translated into a high level architectural design for the SIM. A High Level Design/Low Level Design methodology and wider project documentation set was introduced and the High Level design work was continued through the Autumn of 2012 resulting in the production of an Architectural Design Document (ADD) for the SIM at the end of December 2012. Following ADD Review, the Low Level Design Phase commenced, with code production occurring in parallel with Detailed Design Document (DDD) preparation work being carried out through 2013 and the first half of 2014. This included the preparation of a network database (the Authorised Network Model) using further data management specialist staff from contracting partners CGI. Working with WPD data management staff and using WPD Production/ business as usual data repositories and systems as sources, the data model and schema were first derived and documented and then the Authorised Network Model database itself populated with contents was prepared. The Authorised Network Model production and Data management issues are described in Section 5 below.

In parallel to both the lower level design/SIM code production and Authorised Network Model Network data preparation, a further project workstream relating to Load Profile production according to the high level Demand Scenario models was being undertaken as a further parallel activity. This FALCON activity is documented elsewhere (see Load Estimation Report)

Integration commenced once the bulk of the systems were produced but proved problematic and took longer than expected, pushing back the availability of a fully integrated SIM system to much later in the programme than originally foreseen and planned. The decision was taken to persist as far as possible (in the face of these integration issues) with the originally intended albeit delayed plan, and not to limit core functionality or other aspects of the SIM as an expedient. However, as planned, the project delivered the concept of an initial SIM prototype version, which may be used by the project team and WPD experts to meet the FALCON project objectives.

An approach of continuous integration was adopted by IVHM using automated systems. Code control and issue reporting and management was effected using Altassian BITBUCKET while cooperative working was facilitated by adopting Google Drive/Google Docs for the management of shared documents and Sugarsync / WD MyCloud as a shared file repository, all approaches that were especially important with a distributed development team.

The system development environment was split between TNEI and IVHM, with TNEI concerned mainly with applying the introduction of a number of enabling changes in the IPSA system kernel (which would be of use to multiple TNEI clients), the implementation of the intervention techniques and the production of a set of API routines located in an *IPSA Wrapper* layer responsible for interfacing to the SIM Harness and exposing the main IPSA electrical engineering functionality to the wider SIM. This development work was conducted on TNEI's own in-house production facilities with IPSA product work constrained heavily by product development and maintenance timescales and requiring in some cases the issuing to the project of intermediate BETA releases of the IPSA product.

The role of IVHM was to develop optimisation harness around the IPSA network modelling engine (SIMH), user interface for experiment management, and handle integration of the SIM. At IVHM a dual server host platform was prepared and deployed for both development and operational hosting of the SIM. At the same time, desk based code authoring and unit testing was conducted on powerful desktop computers and additional desktop devices were also adapted for integration, test and documentation purposes. At the outset it was not known how much demand on computing resources would be made by the Running SIM system conducting a full experiment, consequently a generous specification was assumed for the host platforms and parallelism assumed for the SIM Experiment RUN phase using multiple host computers. Because the architecture had to be collapsed onto a single host (while back end – GUI interface data volumes were optimised) it was necessary to perform the SIM production RUNS, which gave the results for this report, on a bank of four high spec desktop PCs.

3.2 SIM Development Pathway

At the outset of the FALCON project the SIM was foreseen to be a single threaded development resulting in the production of a prototype. The further development of a business tool was envisaged if this prototype proved successful and gained the confidence of the target users. A user group was set up so that the development project could respond to feedback from engaged users to refine the prototype tool where necessary.

3.2.1 Optimisations Undertaken

The development approach took a pragmatic stance between maintaining a clean system design and optimising for performance. It was known from the outset that the extent of the data both underpinning the SIM as well as generated by it would be significant, and this was indeed the case. The simple fact of the data extent and the demands this could naturally place on memory in particular meant that some careful optimisation was needed. The largest data repositories were:

- The Authorised Network Model. This was mainly an issue for storage and management of the base network for the whole area that the SIM could be asked to consider, in practice however the SIM selects only a small subset of the available network area (say, surrounding a single primary) on which to base an analysis, so this was managed by selecting the size of the analysis area to suit the capabilities and limitations of the prototype;
- The load profiles. These were by far the largest data element principally because of the need for variants of each of them (to cover different characteristic days within a year and to have up to 35 years to the time horizon) but also because of their intra-day half hour time resolution and the need for a distinct set of these for every substation location. While a SIM RUN addresses only a year at a time (limiting the

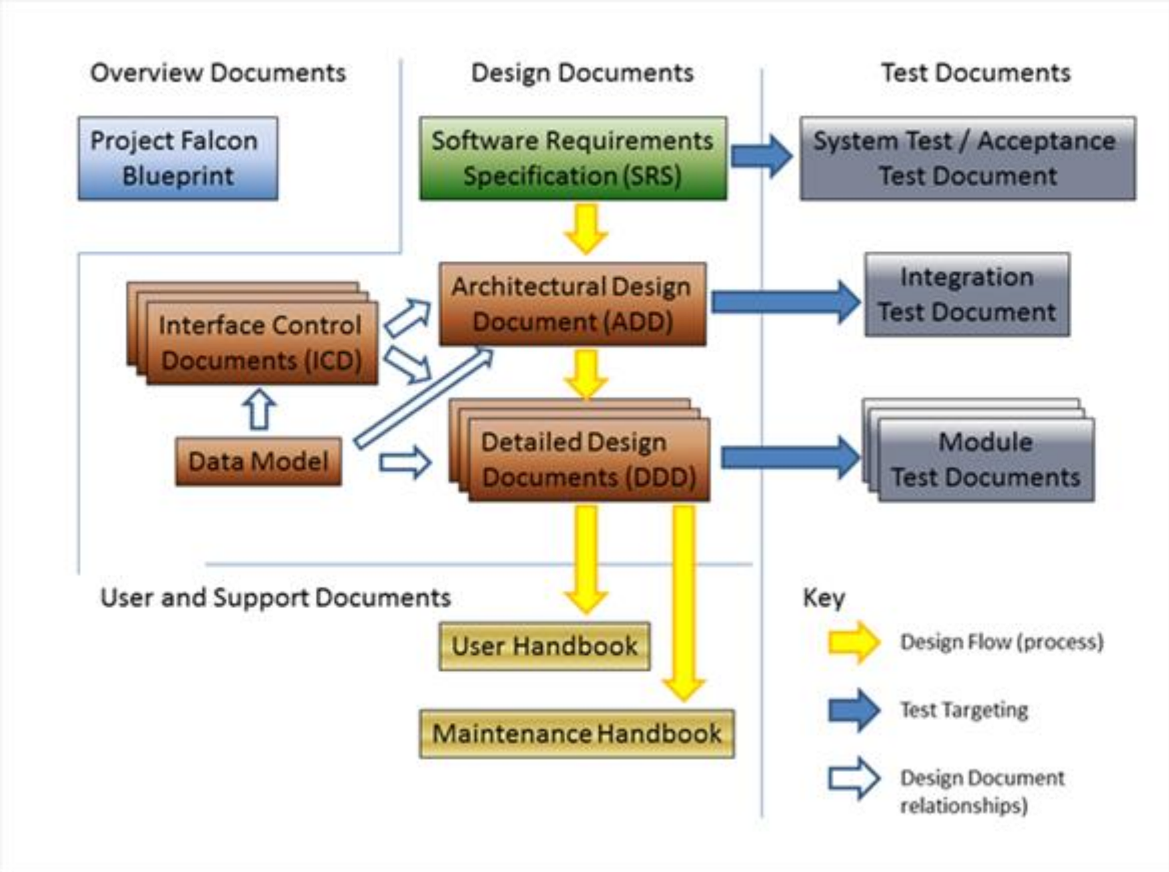
extent of the total load profiles needing to be available for access in this phase) the result display function of the SIM might draw on any load profiles in the entire set for the analysed network area. Thus to allow results display to even be possible, it was found necessary to pass load profile data on the various SIM internal interfaces using a file based rather than a memory based mechanism. This approach also optimised the SIM for handling the analysis of larger network areas. The adjustment itself was made during the integration/validation testing phase when attempts to display computed SIM results with multiple years of extent failed on “out of memory” issues.

- Network states. A network state is a large data entity used as a basic computational device by the SIM. It contains, as the name implies, a full self-sufficient and complete definition of a network condition at a given point and it may correspond to a “failed” or a “fixed” status type. Because the SIMH was designed to be stateless, the network state had to remain complete and full.

3.3 SIM Documentation Set

The documentation set defined for the SIM followed a standard project alignment, with Design Overview (Blueprint), Requirements document, High Level Design documents (Architectural Design Document (ADD) and Interface Control Documents (ICD)), Low Level Design document, Test documents and User documents. The Document set and the relationships between them are illustrated in the following diagram:

Figure 8: SIM Documentation Set



Source: FALCON SIM Documentation Plan

3.4 SIM Key Design Principles

The design of the SIM was based on a number of key design principles, which were identified and listed at the Architectural Design stage of the project and which are listed below. The intention was to provide a guiding framework for the SIM implementation to ensure consistency of approach and to anticipate where possible the key difficulties that might be eased by taking a managed approach. The guidelines were maintained through the build phase but a few had to be tailored to fit project imperatives (principally associated with timescales and scope). The main principles were:

- Proven electrical modelling system at the core. IPSA was chosen for its extensibility;
- Optimisation for Performance. With significant uncertainty over processing times at the project outset it was necessary to take a very careful approach to this during the SIM implementation;
- Design for parallel processing; Minimise number of data transformations in Run-time;
- Minimise number of external interfaces. Other SIM principles however pulled in the opposite direction, for instance the implementation of a stateless system requires

data (and this is extensive in constructs such as the *network state*) to be re-read at each new entry point;

- Split Complex User Queries into Simple Experiments. Complex user queries that would otherwise require simultaneous analysis of multiple primaries, cost models, connection options, etc. are split into relatively simple experiments (RUNs). The results of each RUN are stored in the persistent Results store. There are several reasons for that choice: Simple experiments allow for a Search subsystem that is easier to implement; A small experiment would be generally computed faster than a larger one;
- Each primary in the 11kV network is relatively independent from the other primaries. While feeders from other primaries may be involved in restoring power under N-1 analysis, there are no permanent meshes operating between the various primary substations. Having persistent Results store enables the Engineer to analyse difference, average or aggregate of multiple Results either from the same of from different Runs. The Engineer will be able to use an external spreadsheet application to develop new types of reports from the "all data" report supplied by the SIM;
- Localisation /Modularisation of Encapsulated Intervention Technique Code. To allow the SIM to possibly be extended with new intervention techniques in the future and to simplify modification and refinement of the existing ones, the technique-specific code was localised in few places. The business logic of the technique models is therefore contained within the specific "*Produce all possible applications of intervention techniques*" block of the Search module. Additional data that might be required for some techniques is stored in the Generic Run-wide Data store, a reference to which is passed to the technique models. Based on the information about network failures, a technique model determines whether the failures are fixable by the technique, optimise location and size the applications;
- The SIM Harness is stateless. The SIM harness was designed to be stateless in support of a multi-threading capability. This has the drawback however (with performance implications) of requiring data to be re-read on every pass (nothing can be preserved or assumed in respect of a previous system state). The one issue arising from this approach was however the stateful condition of IPSA – needs further development;
- Clear Separation of "Network Modelling" and "Costing & Optimisation". All functions that require interaction with the network model, such as power flow and fault level analysis, modifications of network topology or asset parameters and displaying the network model are performed by NMT or NMT-derived tools. On the other hand, costing of interventions, guiding the search and browsing of results is performed by the SIMH component. This allowed reuse of the maximum amount of existing NMT functionality as possible. Likewise, most of the changes in NMT will form part of its core functionality in the future, thus reducing the number of bespoke NMT functions, which would be difficult to maintain;
- Unification of the User Interface Presentation. The Editor functions were designed to provide, where possible, a single unified approach to data management, with the IPSA (NMT) custom data tag used to differentiate between the different classes of data

manipulated by the SIM and handled through the Editor Function. Thus cost models, load profiles etc. were identified as such within the data using these extended attributes allowing the same Editor function for the Network and Patches to be utilised across the SIM. User Interface "Look and Feel" Elements of the user interface of the SIM are contributed by the NMT component and the SIM Harness (SIMH) which encapsulates it:

- Network Data Manager (NMT);
- Editor (NMT);
- Result Visualisation Tool (NMT);
- Experiment Planner (SIMH);
- Result Browser (SIMH).

As the NMT elements already existed prior to commencement of the FALCON SIM development, the SIMH user interface had to be designed to align to the extant screen layouts and behaviours as far as possible. The initial plan to use exactly the same widget library (Digia QT) was however abandoned when the decision was made to implement the SIM User Interface in a captive browser window system. This approach to move to the use of a captive browser was done with an eye to future SIM development given that TNEI have an aspiration to move the user interface for IPSA to become a browser based system. Thus GUI convergence across the whole SIM is therefore expected to be better in the future;

Use of colours, naming conventions, behaviours, layout and general appearance were coordinated and harmonised across the user interface where possible thereby ensuring that the user experience and general ergonomics were in-line across the whole SIM user interface. A user pilot group was used for steering / advising the development of the SIM user interface (and other aspects) through the detailed design and implementation phase;

- Prototype Proof-of-Concept. The SIM was designed as a prototype proof-of-concept system, principally because of the need to explore fully the following considerations: The size of the design space and the expected number of results per simulation Run was uncertain; The approach embodied within SIM called for a number of new business processes or major adjustments to the existing ones; Computational feasibility of the approach had to be studied and the right balance of simplifying assumptions versus execution Runtime, the precision and reliability of the results (and the implementation time available to the project) needed to be determined; The SIM would use six novel intervention techniques, supplementing the "technique" of traditional reinforcement to help to resolve network constraint violations. One of the main FALCON project objectives was to study and analyse those techniques. Consequently, the SIM in prototype form must be operated by technically and computer literate users;
- Error Condition Handling. The SIM was designed to be able to handle "expected errors" such as incorrect user input, etc. As part of this handling, the SIM is tolerant to minor problems in source data, providing user notifications, defaults and with an in-

built ability for the user to manually correct an error where appropriate. As a prototype system, the SIM is not expected to automatically recover from failures (e.g. out of space in the DB, voltage collapse, etc.) Instead, the SIM provides exception handling for all operations and a global logging facility to capture all software failures. Irrespective of the above, the SIM has been designed and coded to be robust and reliable and all possible steps are taken to ensure that the code is as stable as possible even under stress, with as many error conditions as possible being anticipated and adequately dealt with;

- Modelling Scope. The SIM models the 11kV network from high voltage side of Primary Substation transformers (in the FALCON area this will be the 33kV side of the 33/11 kV transformer) to the Low voltage (LV) side of secondary substation transformers. The network from the secondary substation to the customers is not modelled. The network between Grid or Bulk Supply Points and the high voltage side of Primary Substation transformers has been represented by an equivalent network;
- In principle the SIM could be used at any voltage level, however matters such as visualisation (which in IPSA for example uses colour to represent different voltage levels) would need special attention were this to be changed beyond the current pilot functionality. Similarly there would be work required to provide the Authorised Network Model for other voltage networks as well as changes in how load estimation was applied for LV networks etc.;
- Self-Consistency of Input Data. Whenever an input data store requires the data to be sourced from external WPD data stores (e.g., Authorised Network Model) or third party providers (e.g., load profiles), a batch process for importing such data must exist. The batch process extracts the data from source, transforms and then cleanses it and prepares for initial loading into the SIM. The batch process must perform post-processing quality check of the data to ensure that the data is self-consistent. Only self-consistent data can be inserted in the input data stores by the batch process.

3.5 SIM Development Support

To produce the SIM it was necessary to provide the programmers with the capabilities necessary to design, code, control, build, test, log bugs & errors and create Wikis and carry out cooperative working. A number of tools and environments were identified and then used to achieve this objective.

Source code for the SIM project was stored in a multitude of GIT VCS repositories with current integrated code being available in the “main” branch of a repository on the Bitbucket system. Bitbucket also provides WIKI and message board facilities as well as Issue recording and annotation.

IPSA/NMT IPSA wrapper code is stored in the “ipsa_wrapper” repository which mostly contains code directly supplied by TNEI as NMT supplier.

Integration tests have been stored in a specific “integration tests” repository.

In order to simplify future development environment instantiations, no Integrated Development Environment (IDE) is deployed to the project. Instead, a relatively simple text editor (Sublime Text 2) is used for source code edits and a set of Bash shell and Python “toolchain“ scripts were developed to aid with common tasks like Running tests or deploying the SIM Harness.

Toolchain scripts are expected to work only on the target OS for the particular project. For Virtual Machines that is CentOS, for host while GUI code is designed to operate on Windows.

To aid in file synchronisation between host and VM, an ExpanDrive is deployed to speed up the development process.

The development is performed on a Windows host computer with a CentOS-operated guest VM. The code is modified on the host, it is then uploaded to the VM and executed there. There are local RabbitMQ and PostgreSQL servers permanently installed and Running on the guest VM.

The development computers are Windows 7 x64 machines with CygWin installed in order to have ability to Run Bash scripts if needed. The UI is Run on the host (Windows) machine with the RPC back-end being configured so that it connects to the VM-hosted RabbitMQ server. The frontend relies on the backend to be operational and connected to the same RabbitMQ server and vhost. The computational part of the SIM is performed by the backend Running on the VM on the development machine host. The host platform can thus be a single machine or client server pair separated over the network. The network operation of the SIM was however found to be impaired by the large amounts of data in the initial prototype SIM version. The largest data component is the Load Profile (LP) set

3.6 Choice of SIM Technologies

A number of choices needed to be made in implementing the SIM, operating within a number of constraints which acted to limit these choices. The constraints included:

- The possibility of future deployment within WPD necessitated a meeting to establish the nature of a potential future deployment environment and processes to be followed for possible later adoption within the business. A meeting was therefore held with the WPD IT department (WPD/IR) very early in the project. This limited the main user interface to tools and systems able to be supported by Windows 7 (at that point) however server side functions/hosting was less constrained;
- Availability of Open Source platform facilities favoured by educational establishments such as IVHM who were responsible for most of the development and had extensive familiarity with these tools;
- An open source messaging system was used to support the distributed (client-server) nature of the overall SIM environment;

- IPSA was available as Windows and Linux versions however the overall system needed to be developed bearing in mind that IPSA was a pre-existing product;
- With the SIM expected to be computationally intensive, the hosting environment for the server side components was initially chosen to offer the best options available for the price in terms of processing power and memory – allowing for the deployment of a virtual machine platform,

3.6.1 Use of Python

Python provided a reasonable compromise between execution times, speed of development and familiarity to all FALCON Project team members. Python is fast in terms of development time and also integrates well with several NMT planning tools. It was already available as an interface language to IPSA and fitted well with the requirements of the overall SIM implementation team. While it would of course have been possible to use other languages this would have delayed the programme due to the time required to implement the alternative interface.

The primary drawback with Python was actually the relative shortage of full featured IDEs for Python. For a next generation SIM system any statically-typed language with extensive statistical libraries could be preferred: Java, Go, C# or C++ though this would clearly require a suitable NMT with the necessary bindings.

Python also provided sufficient versatility for the Project and allowed much easier evolution of the NMT/SIMH API interface specification.

3.7 SIM Host Support Infrastructure

During the SIM Detailed Design phase the method for hosting the SIM was defined, documented and then implemented. This required careful attention to such issues as choice of operating system, choice of implementation languages, virtualisation, messaging and inter-process communication, databases etc. This aspect had only been briefly considered at the Architectural level which was concerned principally with the SIM functional elements.

As the full SIM experiment computation process places a significant strain on the hardware, it was decided at the start of the design process to perform this on a server platform while providing users with a thin GUI client that can access the computational backend via an IPSec tunnel or a VPN.

Thus, the SIM operational environment can be viewed as being logically separated into two parts: a computational core and a user interface (UI). The actual physical deployment of the SIM in a given environment is highly flexible, may vary, and can be tailored to the specific requirements of a given situation. Thus, in a full client/server deployment – the full host server environment may be used to host the core (engine) while remote client laptops or desktops may host just the GUI elements. In such a deployment scenario:

- All VMs are Running on the Cranfield FALCON server with clients connecting to the server via VPN;
- Client computers only have the UI component installed. The component connects to the RabbitMQ server Running on the Cranfield FALCON server. As the computational/data VMs are Running 24/7 connected to the same RabbitMQ server, the client gains capability to send data and perform RPC calls on the FALCON server VMs.

Alternatively, the entire architecture may be collapsed down onto a single host. In such a case all parts of the SIM Harness backend are run on a single virtual machine (that is executed on the same host as the GUI frontend) with Rabbit MQ and Database servers being hosted on the same VM. This was done during the main integration and test phases with multiple parallel SIM instances set Running on a bank of “servers” (which were in fact high end specification PC units).

The main parts of the SIM Harness in the distributed architecture were designed to interact with each other exclusively via the messaging server, so that no part needs to possess information on the location of any other part. The only hard requirement is for all parts to be able to connect to the same messaging server and interact via it. Some file based interfaces do exist however as a result of constraints on available memory – it was not in the end possible for all relevant state information to be held in memory so this had be passed indirectly.

It was also found during the integration testing phase that it was useful to be able to capitalise on the ability to collapse down the SIM architecture onto a single host and then to run multiple parallel instances of SIM test units. In such an environment the full network message queue was not required and the project therefore included an option to “short circuit” this out in such instances to improve performance. It is seen therefore that the SIM hosting environment is highly configurable and can be adapted to suit the prevailing conditions.

3.8 Some SIM Statistics

In this section we present some statistics relating to the prototype SIM and the development that produced it. This is intended to give a feel for the size and complexity of the SIM software system.

Table 1 - SIM Statistics

Item	Number	Comment
SIMH lines of code	25,098	Multiple components, refer to expansion table below.
Bespoke IPSA lines of code	18,300 total, 15700 for the IPSA wrapper.	Multiple components – Core IPSA was enhanced as a product offering by TNEI to include a number of FALCON initiated changes but more specifically, the IPSA Wrapper is listed here as the FALCON specific part of the NMT. Lower figure excludes wrapper test code and IPSA core code changes.

Item	Number	Comment
Integration Issues raised/resolved	295	Programme "metric". This will increase as more issues are located and resolved
Authorised Network Model number of primary substations in core trials area	6	Marlborough St, Childs Way, Fox Milne, Bradwell Abbey, Bletchley, Secklow Gate.
Authorised Network Model Number of secondary substations in core trials area	579	Core area substations.
Authorised Network Model Number of substations in peripheral area to the core trials area	1,155	Needed to manage adjacent feeder issues when transferring load and meshing.
Authorised Network Model raw database size	212MB	Raw size of Authorised Network Model Access Database, refer to expansion table below.
Load Profile database annual set (curves)	1,123,632 CSV Files	18 characteristic days, 36 years (2015 – 2059) for 1734 substations (per demand scenario)
Load Profile database annual set (datapoints)	53,934,336	48 data points per day curve (half hourly datapoints)
Load Profile database size (per demand scenario)	~3GB	Size on disk (per demand scenario)
Number of base demand scenarios	4	DECC1 – DECC4. Additional variants (around 5 further sets).

Table 2: SIM Lines Of Code by Functional Area

			Lines of Code		
Module	**Purpose**	**Type**	**Python**	**sh**	**csh**
Worker machine	A VM that actually calls ipsa_wrapper and performs evaluations	Functional	1249	0	0
MCP machine	High-level experiment control functionality (experiment start/pause/delete, etc)	Functional	266	0	0
GUI machine	Not actually a VM, but a piece of code that is Run on the client's computer that starts up a web server providing UI services supporting user interaction with the SIM.	Functional/GUI	3481	0	0
IPSA_wrapper	ipsa_wrapper - Interface layer managing the communication between the SIMH and the core NMT (IPSA) and also implementing bespoke code not inside core IPSA (such as technique modelling)	Functional/NMT	18288	12	0
Libmsg	Handles data transfer between SIM harness machines	Infrastructure	5427	139	21
Libdata	Sits on top of the libmsg, provides facilities to access db data for all SIM Harness machines except the "orm" machine (that machine actually serves as	Infrastructure	5220	139	21

			Lines of Code		
	data server for the libdata module)				
Host machine	Code nominally Running on the server that hosts VMs. It provides facilities to replace VMs with newer VMs with an updated code and manages the pool of Running VMs (e.g. MCP machine can request more 'worker' instances to speed up the execution)	Infrastructure	6175	325	0
Build machine	A VM to generate CD disk images (ISOs) to be used to spawn a next generation of VMs	Infrastructure	2635	0	0
Totals			**42741**	**615**	**42**

Table 3: Authorised Network Model Sizes

Authorised Network Model Element	Size
Asset Types	44
Imported Crown Assets	4667
Distribution transformers	927
Primary Transformers	24
Switches	78
Circuits	158
Sections	7020
Lines	2193
Coordinates	215,353
Sites	2027
Branches	7011

Source: Authorised Network Model Database

3.9 Key Conclusions

The design converged very quickly around the central concept of an NMT in a harness which directed (via a middleware "Wrapper layer") the otherwise static type analysis of the core IPSA product to derive an evolutionary view of the network through multiple iterations of analysis. The design emerged readily from this, yielding components concerned with initial network set-up, experiment direction and finally results visualisation and management. These system components also partitioned nicely into server and client side functions. The host platform similarly dropped neatly out of the design with hardware elements for the server requiring high specification and a Linux software environment while the client side was constrained by the planned BAU environment being Windows.

Data was critical to the SIM and takes three main forms:

- Input network, cost and load data;

- Output Results Data;
- Supporting data.

Data volumes were very large and dependent upon linked processes and facilities to both generate the inputs (Load model, network (Authorised Network Model), Cost sourcing) and manage the outputs (database, analysis and visualisation/inspection tools). The large volumes of data also required an approach to be taken to interface handling (data exchange) which utilised files as the principle exchange mechanism to avoid memory usage being too large.

3.9.1 Main Findings from Testing

The project deployed a level of automated testing to ease the early stages of integration on the project. This included some GUI test automation tools. Integration testing followed more classic profile of assembling increasingly more complex component sets and testing these, though the SIMs own complexity levels leant themselves well to conducting tests at ever more increasing levels of integration. The path followed was incremental and iterative (repeating stages as necessary as bugs were found and cleared to ensure regression testing was carried out effectively) and included these main outline stages:

- Deploy traditional reinforcement technique only in a SIM Run over two years on a single Primary Authorised Network Model area with a reduced load profile set having only two characteristic days;
- Try further techniques to flush out immediate issues;
- Try larger network areas before reverting to one Primary Authorised Network Model area;
- With traditional reinforcement technique only - do a SIM Run over multiple years with a reduced load profile set having only 2 characteristic days;
- With traditional reinforcement technique only - do a SIM Run over multiple years with a full load profile set having all 18 characteristic days;
- With each technique in turn - do a SIM Run over two years with a reduced load profile set having only two characteristic days;
- With each technique in turn - do a SIM Run over multiple years with a full load profile set of 18 characteristic days;
- For all techniques - do a SIM Run over multiple years with a full load profile set of 18 characteristic days;
- Repeat the above with the full six Primary Authorised Network Model area.

To speed up testing as described above, an approach was taken to try to limit the elapsed SIM execution times in this phase by limiting the processing load using the following mechanisms:

- Use only two characteristic days of the 18 available;

- Use a subset of the 48 diurnal load points.

Between them these two actions could have resulted in a reduction of around two orders of magnitude in the size of the input data set and greatly speeded up potential for testing different scenarios. The multitude of load profiles in the full dataset simply forces the IPSA processing to do more work (more of the same). Unfortunately it was found that it was only possible to utilise the first of the reduction methods as there is an intra-day dependency within the technique processing, meaning that diurnal load points could not be reduced.

1. Many existing Network Modelling Tools are designed around a workflow involving constant interaction with the user, which exercises them in a different way when compared to the high performance automatic execution within tight processing loops inside the SIM. Consequently, their day-to-day performance may not serve as an indication of their performance in the SIM setting;
2. Whilst an Electrical Engineer using one of the planning tools available today may have high tolerance for software errors and inefficiencies a SIM like tool needs to be based on an underlying software base from which software errors have been excised as far as possible;
3. Contracts and commercial documentation (created on FALCON during the negotiation and partnering phase) need to include adequate Scope of Work (SOW) specifications for the various participating organisations in a software development project workstream;
4. Choosing a mature product as the base of the NMT kernel rather than writing a new core facility to carry out this function did minimise risk overall and make for a cheaper solution with the downside being that a considerable body of non-essential software became included by default in the overall system. Perhaps 80% of the NMT system was comprised of software that would never be required in the SIM. This extra code is an overhead as, for example, bug fixes in the "unused" 80% might cause new releases of the kernel to be made – resulting in ongoing programme management overheads and potentially system instabilities;
5. Management of a distributed development team is well known to require close supervision and needed special attention throughout the FALCON Project. While a good set of design documents was developed and the project utilised shared working tools such as Google Docs (cooperative working and document management), Bitbucket (cooperative working and code management) and Sugarsync (file repository), periodic collocation of the team was needed to promote a thorough understanding of the position at some points in the project. This was particularly the case during integration;
6. Collaborative working tools included in the Bitbucket configuration control system were used by the project to manage code. Teleconferences and face to face joint working sessions can also be advantageous to move matters on faster and avoid some of the misunderstandings and cases where it was assumed matters were in-hand when they were not always so;

7. With a good design framework – it became a routine matter to turn the handle to produce the code for the system. As ever, most misunderstandings come on the interfaces so these were carefully specified;
8. The original requirements were well specified and tracked using simple spreadsheets. This is an area which could be improved in the future by use of specific Requirements Tracking Tools;
9. When running tests the individual intervention techniques had been tested in isolation. These were found to not always produce "results", however such stand-alone intervention strategies would never take place in the real world or indeed by applied by the SIM which seeks to deploy the best options in combination from amongst those available. Additionally, techniques would never be applied without being backed up by the capability to deploy traditional reinforcement of assets. Stand-alone technique deployment in the SIM is therefore a testing only facet and would cannot be expected to yield representative results;
10. The cost model data management interface was not fully integrated with the SIM. In common with the main data management functions which were implemented as external facilities supporting the SIM itself (Authorised Network Model, Load Profiles), the cost data was assembled from source spreadsheets obtained from the business into a cost model spreadsheet from which the cost data could be managed and exported to the required CSV formats. This made cost data modification somewhat disconnected. A better approach, and one which might be used for any future BaU SIM, would be to create a more integrated SIMH cost management GUI component;
11. Performance was a key issue and at the present time using the prototype SIM only very localised network investigations can be undertaken with the SIM. This would be a key focus area for a future SIM usable by Strategic Planners, though not for the local 11KV planners engaged on the SIM User Group where the network size capabilities of the prototype are already sufficient for their needs. Runs needed to be conducted overnight and even over the weekend to conduct the longer Runs out to 2050 and more parallelism, software optimisations and/or more powerful host computers are certainly required for future SIM developments.

SECTION 4

Software Nodal Modelling of Evolution in an Electricity Distribution Network

The nodal modelling of the network is distinct from the development of the SIM platform itself as a software implementation project, as described in the preceding section.

4.1 Background

While there are several commercially available Network Modelling Tools available (and in widespread use) the SIM offers the new capability of allowing DNOs to project the evolution of a complex network model at the detailed nodal level rather than just modelling it in the immediate mode. This detailed bottom-up modelling contrasts with the top down approach of network evolutionary models such as the Transform Model developed by the DNOs with EA Technology, although the two approaches should converge somewhere in the middle ground.

The SIM works by directing a captive Network Modelling Tool at its core (in the case of the SIM pilot proof of concept system this was IPSA from TNEI) to execute a directed search loop over a series of many iterations evaluating network states, applying selected engineering and commercial techniques to fix constraints caused by evolving load at the evaluation nodes and thereby generate new network states for further expansion if warranted. The SIM follows the network though a number of evolutionary pathways as it explores the constraint/fix strategies to find the most promising of these pathways using a direction based principally on cost - which includes values for items which are not actually financial items, like network performance or customer disruption.

4.2 SIM Main Assumptions

With a software system as large and complex as the FALCON SIM it is necessary to employ a number of assumptions in order to simplify the implementation and formulate a workable solution. These assumptions cover known and/or anticipated situations as well provision for some uncertain aspects of the system. Furthermore there are explicit and implicit assumptions in play – the former being such as those listed below and described elsewhere in this document, the latter being potentially a more dangerous case. Implicit assumptions can sometimes be made without this being known or their impact fully appreciated at the time.

We discuss below those explicit assumptions that we have marked as being key to the system development.

- **Performance Criteria are Transformed into Cost**. Single objective formulation of the optimisation problem simplifies search algorithm and interaction with the users. In particular, the Engineer is presented with a ranked list of Results and is not required to analyse trade-offs that would be produced in a multi-objective scenario. At the same time, aggregation of multiple performance criteria into a scalar-valued cost indicator loses a significant portion of information about the search space and leads to premature discarding of alternative solutions. The SIM implements a modular approach that permits to change the optimisation algorithm without modifying the high level architecture of the system.

- **Network Change Planning**. The SIM assumes that the atomic planning horizon is within the resolution of a single year, and while the load profiles are expressed using 18 characteristic days spanning the seasons, there is no finer resolution at less than a year in terms of the modelled scenarios. If a finer time resolution is required for a future SIM, this could require significant restructuring of the SIM internal architectures.
- **Independent Primary Modelling Approach.** Currently there is very little load sharing between 11 kV primaries. Consequently, it is possible to assume that applying an intervention technique in one primary does not affect load profiles in other primaries. However, with different primaries becoming more interconnected as a result of applying novel intervention techniques such as ALT and meshing this might change. If a capability to quantify effects of interventions for adjacent primaries will be required for a future SIM, this might require significant modifications to the architecture or computational performance of the SIM.
- **Proof of Concept.** The initial SIM version has been developed as a proof of concept and not as a full commercial implementation necessarily available for immediate BAU deployment. System quality, testing and reliability were at a level allowing a well-trained and informed “power user” to use the SIM to complete the tasks outlined in the use case documentation and to validate the pilot system. A level of software failure above that associated with commercially released systems was therefore deemed to be acceptable. This assumption is explicitly stating a prototype limitation and doesn’t require additional clarification. It is thus clear that a future SIM developed into a product or fully operationally important system would require additional attention in some areas;
- **User Access.** All user classes have access to all functionality. As a prototype system - again, this is explicitly referring to an accommodation in the prototype in terms of handling users in a simplified form. For a production SIM user handling would likely need expanding in terms of capability or to simplify the user interface for the users so that they might not be presented with irrelevant options;
- **Reactive Application of Intervention Techniques**. Intervention techniques in the prototype SIM are applied only when a failure is detected. Potentially the SIM could be enhanced to work in a mode other than in this reactive manner. This simplifying assumption was made to reduce the extent of the search space.
- **Load Profile Structure.** 48 half-hourly interval data point values across 18 characteristic days are assumed for the load profiles. Again, the time resolution and number of characteristic days could be enhanced, but this would have required changes to the load estimation workstream and in the techniques and it is not clear what value would be added. Input data volumes and SIM execution times might be increased significantly by any increases;
- **Deterministic Demand Scenarios.** There are assumed to be no random probability distributions for factors affecting energy demand. A demand scenario is obtained by using a fixed set of values pertaining to various factors affecting load changes in the future.

- **Obtaining a Solution.** A "good enough" approximation (based on standard convergence metrics) of the optimal solution is an acceptable answer. The search space is large enough to make exhaustive search impossible. Introduction of exhaustive search would potentially have significant impact on resource usage and execution times. Any future decision concerning revision in this area would need to take into account the conclusions emerging from the use of the SIM prototype;
- **Trials Linkage.** There is no real-time connection between the SIM and the trials data gathering function of the FALCON project. A future SIM might work in a closed-loop fashion with trials data processing, though an additional external (to the SIM) system would probably be preferred. The value of such a modification is not clear at the present time;
- **Inclusion of Carbon Benefits Computations.** The originally considered incorporation of carbon benefits computations into the SIM was not implemented during the design phase. The reasons for dropping this included the amount of input details required to support the facility and the investigative work that this would also require. Additionally, the general perception was that the direct carbon benefits would be small. The SIM is an enabler for low carbon technologies, but does not directly impact carbon emission in a significant way. This is a possible future "BAU SIM" enhancement however;
- **Handling of Fault Level Constraints.** Handling of Fault Level Constraints. The SIM does not address and remedy fault level constraints. The SIM operates on thermal power and voltage constraints. Currently the SIM identifies fault level constraints but does not model any techniques that improve fault levels. This is a limitation that could be adjusted in a future SIM if required and might constitute an area for further investigation;
- **Data Interface.** There is a simplified data interface in the SIM - much data will be in flat files and where ordered records are required, the data will be managed as a support function rather than being end-user editable. For a 'BAU' SIM better integration and data management would be expected and could readily be added;
- **Operational Cycles.** Intervention techniques should have at most 1-day operational cycles, e.g., a battery should be at the same charge state at the beginning and the end of the day. This may potentially reduce effectiveness of some techniques (e.g. batteries) in N-1 conditions, although following consideration currently it is not viewed as introducing any particular problems as the change between days happens during midnight, which corresponds approximately to the time when the network is in its least onerous condition regarding both demand and distributed generation. That means that the techniques (such as batteries) have plenty of time to reach a steady state before the end of the day. In the future, however, the situation could be different. It is possible to conceive that with the proliferation of EV that the demand peak will occur between 1900 and 2400, meaning that is the time when batteries should discharge. The battery technique should in such a case implement some advanced logic to verify that the battery would be able to charge sufficiently during the following day. The current arrangement also prevents the use of techniques to

mitigate 'once in a lifetime' scenarios, such as Christmas, bank holidays or other similar events, which would not allow the batteries to recover during the same day, but the following day with presumed lower activity would afford such an opportunity;

- **Intervention Technique Implementation.** Intervention techniques have been designed with computational complexity anticipated and minimised where possible through simplification and optimisation. It is possible that should it become a requirement for additional accuracy in SIM outputs, such simplifications may need to be removed or a more complex technique algorithm be designed and implemented. Certainly being modular, more complex or even completely different intervention techniques can be added to the SIM without too much work, however as the assumption implies – there may be an adverse impact on SIM execution times or placing more complex requirements for additional data necessary to drive enhanced techniques. SIMH passes a list of allowed intervention techniques for each year of analysis to NMT/IPSA to guide the application of intervention techniques. The list of allowed intervention techniques will be set by the Engineer in the Experiment Planner;
- **N-1 Conditions.** N-1 conditions start at midnight and last for the whole day. This assumption is linked to the overall simulation granularity of the prototype tool. Doing anything else is likely to have a significant impact on the SIM design without any clear advantage being derived;
- **Search Function**. The search function assumptions are that given a network state with a failure, each intervention technique model would produce around 20 applications or around 100 in total for all techniques. There is no inherent limitation in the SIM on the number of technique applications, but this assumption gives some pragmatic bounds;
- **Processing Rules.** When fixing a failed network state, an application of an intervention technique is evaluated until either a new failed network state is produced or the end of the evaluation period is reached. This is done to maintain a consistent cost function for A* search. The NMT will perform one year of analysis based on the network, plus all network patches supplied by the SIMH for that year. Any different granularity could be considered but the value of any greater time resolution would need to be determined. The NMT will generate a separate patch file for each reinforcement technique that it applies. These will be passed back to the SIMH as part of the results for that year of analysis;
- **Assimilation of Manual Patches.** Prior to the search being conducted by the SIM, an IPSA data model will be generated for every year of the analysis with a change by applying manual patches to the authorised target network in that year. (Considered alternative: a single network model with incremental changes for every year of the analysis). Each yearly model termed as network state will include load profiles for the respective year of analysis;
- **Generation of Automatic Patches.** As a result of applying intervention techniques, a technique patch will be created for each application of the intervention technique linked to a yearly version of the target network;

- **Asset Groups.** Two levels of asset groups are defined, namely, 'meshed feeder' and 'asset'. A third kind of asset groups, 'feeder' was considered, but deemed impractical because of feeder topology changes in N-1 configurations. Consideration of potential feeder topology changes in N-1 configurations may be too complex, but might be considered. The benefit might be derived from this is a subject for further discussion;
- **Network State Metrics.** CML/CI, losses & fault levels are meaningful only for network with no issues, therefore, those are calculated for intact network with no constraint violations only;
- **Authorised Network Model Store**. In the SIM the Authorised Network Model is initially be limited to WPD's 11kV network in the Milton Keynes area, as the current process of compiling the network dataset involves manual operations. The data preparation process aims to automate the merging of the required WPD input datasets as far as is possible. The management of data is a key issue when scaling up the modelled area covered by the SIM, however much of the complexity lies in the preparatory piece of work, outside the SIM itself, to render this data available to the SIM. The SIM is designed to handle very large input networks and associated files however the processing time required to model full DNO areas or large regions may require special data staging platforms to be deployed;
- **Scaled Loads.** These become useful in a number of instances, such as the addition of a dummy load of a certain type. Load profiles are not modified directly. An existing load may be modified by multiplying it by a constant, or adding or subtracting another existing load from it. A load profile for a newly created substation is created by adding / scaling existing load profiles for other substations / dummy substations. Improved data handling might be considered as a later SIM enhancement beyond the prototype as discussed above. It might be possible to add plug-in SIM tools in a future new enhanced SIM version for e.g. a substation load profile generator and other similar utility functions; when scaling load profiles or creating new load profiles scaling factors and references to load profiles' substations are saved in patch files. This ensures that load profile scaling and composite load profiles are applied correctly across all demand scenarios;
- **Network Patches Store.** The annual patches have been created from the Authorised Network Model using the Editor (there might be some annual patches created from the initial data import, but those should be equivalent in format to the ones created using the Editor). Checks will be undertaken to ensure that the selected annual patches result in a consistent network model. Patches that do not give a consistent model will not be applied and the Engineer will be notified. A consistent model is one that allows the changes to be merged in successfully such that all components are correctly connected;
- **Manual Patches.** There is no automated computation of the cost of manual patches within the SIM. The users must address this aspect themselves using the "Editor" when creating a manual patch. Such an improved data management/handling facility, in common with a number of similar enhancements from the prototype SIM could be improved in an enhanced SIM version.

4.3 Supporting Concepts

In order to allow the SIM software system to adequately relate to and model a real-world network we needed to develop a SIM "World View" and ensure that this corresponded to reality. This section discusses these concepts and how they were dealt with by the project. The approach taken in this subsection is to list the real world concepts as rows in a table and cross reference these to a description of the SIM approach taken in each case.

Real World Concept	SIM Approach	Comments
Built Network	Authorised Network Model, Authorised Network Model view at nodal and connection level based on operational sources of this detail represented using the elemental constructs available to IPSA. The supported elements have attributes such as type, subtype, rating, mounting etc.	The network model available to the SIM (Authorised Network Model) is only as good as (and is therefore limited by) the data held in the BAU data systems of the DNO
Nominally operating Network at some future target date	A SIM Result. A "Result" has a specific meaning – being a non-overloaded (and therefore nominal) network – the end-result of a sequence of fixed (repaired) network states obtained at the final analysis year (SIM RUN end point – target year).	The SIM Result (in the formal sense of that word as interpreted by the SIM) is a key concept. It effectively is a crystallised sequence of conditions and operations that have resulted all the way through the evaluated network state progression in a usable network being available at each point. The result is therefore a series of states and includes all of the patches deployed to realise the successful end condition.
Customer Load	Defined *Load Profiles* at specific nodal points implemented as 48 point diurnal load profile curves arranged by 18 *characteristic days*. Load profiles were generated as sets of individual Load Profiles resulting from Running the separately developed *Energy Model*. These sets correspond to specified *Demand Scenarios* reflecting projected views of how demand will develop based on differing assumptions around future customer behaviours.	Load modelling is a complex task and is accompanied by a number of assumptions and approximations. It is limited in its accuracy by the data held by the DNO in respect of the customer types and numbers at a given modelled location but is also subject to factors which are very difficult to model and predict.
Customer Load evolution	The changes to the load profiles resulting from the evolving behaviour of users and application of new technologies on the network. Reflected in adjusted load profiles as generated by the Energy Model. These change in each year (the modelling increment).	There are many evolutionary scenarios and this is why the SIM is required – to evaluate the network response to these different possibilities.
Natural Network Evolution	As networks are not static due to BAU maintenance and planned developments, these adjustments can	Such patch based modelling will become increasingly inaccurate as the timespan increases and is dependent on a number

Real World Concept	SIM Approach	Comments
	be accommodated by including Manual Patches which can be applied to the network at certain points and thereafter.	of factors, many beyond the control of the DNO.
Network Constraint (thermal or voltage)	Network Constraint, IPSA detected overload	A constraint is a condition of the network that affects the structure of the 11kV network and which requires resolution. These may be thermal or voltage.
Network failure conditions	The SIM considers N-1 failure cases and carries out its analysis under these conditions	
Traditional Reinforcement	Traditional reinforcement technique wherein constrained assets are replaced by assets with a higher rating (or else by split of a feeder). The size of the increment depends on the size of the overload. In the real world this is combined with a forward looking projection of likely future demand to try to ensure that the most cost effective upgrade is deployed.	The usual form of remedial action in the current operating paradigm.
Engineering Intervention Techniques (DAR, ALT, Meshing, ES)	SIM applied engineering techniques corresponding to the real world intervention technique as implemented in software and based on a theoretical behavioural or physical system model (e.g. DAR thermal modelling of transformers and cables)	
Commercial Intervention Techniques (DSR)	SIM applied commercial techniques corresponding to the real world intervention technique as implemented in software and based on a theoretical behavioural or physical system model	
Passage of time	The SIM moves through the years specified by the experiment, with a “year” being comprised of 18 characteristic days. Load profiles are available for each year that might be processed and for of these day types within a year. While tests on the 18 characteristic days are sufficient for finding overloads, For some measurements such as accumulating the measure of CML/CI – the number of days of each characteristic type must also be defined to the SIM so that it can compute values based on a 365 day year.	

Real World Concept	SIM Approach	Comments
Power Flow/electrical behaviour of network	Modelled by IPSA	
Cost of changes	The concept of cost in the SIM matches that in the real-world although the former is based on a cost model that maps network components onto elemental costs based around the RIGS classification. Costs are also subdivided into initial, ongoing and per-use classifications – essentially as they are in the business (CAPEX/OPEX view).	There are different ways to view and allocate costs which are in general governed by accounting practice within the organisation. The evolution of costs is also difficult to manage, but these can be viewed as SCENARIOS to be modelled by the SIM.
Network State/condition at a given point	The SIM requires the construct of the Network State. This is a snapshot network condition and contains status information on all entities in the set of network state elements. The network state was therefore a large and central data construct within the SIM.	

In addition to the above concept mappings, it was also found necessary to introduce a number of other modelling artefacts into the SIM which did not in themselves arise from any particular real world concept, but rather were devices needed to manage the software. These concepts included:

Network Asset Groups

When applying a technique to resolve a network issue on an asset where this could have an effect on another asset, then these assets can be considered to be related. Where there could be no effect on the other asset then these assets can be considered to be unrelated. Related assets form network asset groups.

Three types of network asset groups have been identified

1. Each individual asset
2. All assets supplied by one or more feeders (i.e. from the primary substation circuit breaker to the open points on the network)
3. All assets that could potentially be supplied from the feeder (i.e. from the Primary substation circuit breaker through any open point and up to any primary substation busbar).

In practice, only 2 kinds of asset groups were implemented, as asset level asset groups would change every time there is an N-1 condition. This is an important learning point - during validation it was discovered that even the interventions originally envisaged to affect only individual assets, such as cable or transformer upgrade, in fact affect other assets by improving/worsening existing issues, removing issues and creating new ones. Therefore, the whole concept of asset groups is invalid. The same applies for the originally foreseen asset group based patch caching, which was disabled in the SIM during the development.

Automatic Patches

Automatic patches are the collections of adjustments proposed for the network in response to SIM detected network overload conditions and the consequent deployment of remedial techniques to bring the network back into a nominal state.

Demand Scenario

It will be recalled that the name of the SIM is derived as an acronym from its full name which is ***Scenario*** Investment Model. The scenarios in this case are an assumed set of behaviours including responses to emerging technologies and perhaps also drivers such as the cost of electricity as well as other factors including a wish to be green/responsible among some. Thus, the SIM is intended to have the key capability of being able to model the network condition and response to scenarios which envisage these different prevailing conditions.

Customer behaviour manifests itself as the nodal point *load profile* – this is usually considered to be a diurnal curve taken as a self-contained 24 hour unit, with additional seasonal, extreme and weekday variants. The load curves are complex and to model them requires a significant amount of effort. They are complex not least because they are themselves aggregations of many different customer loads attached to that node point (substation), and these customers, as well as being of different types (domestic, light industrial, office, heavy industry, sports arena, school, hospital) also exhibit individualistic behaviour distinguishing them from others of the same type. The production of accurate load curves reflecting different assumed future behaviours and projected responses is therefore attended by significant difficulties and requires a number of assumptions to be made. This theoretical load curve production, with collections of projected future load profiles covering the modelled network area, is however the main driving force for SIM scenario modelling. Collections of such load profiles which attempt to predict load under an assumed set of prevailing conditions are called *demand scenarios*.

4.4 Use of an NMT Kernel by the SIM

The use of a proven kernel NMT system by the SIM was central to the overall approach and drove the design at all levels. The chosen NMT for the SIM pilot proof of concept was IPSA from TNEI which featured not only analysis facilities for power flow and faults at different voltage levels but also provided a fully featured graphics facility for display (and creation – in the case of manual patches) of network elements. The overall approach taken was to place IPSA at the heart of the SIM and to both enhance the kernel system itself but to also supplement this by IPSA "Wrapper" functions. The Wrapper thus provided plug-in capabilities such as the technique model implementations as well as a middleware service layer interfacing between the NMT "kernel" and the higher levels of the SIM provided by the SIM Harness, SIMH.

The approach thus allowed for the strategic enhancement of the IPSA product generically by TNEI for the benefit of all TNEIs IPSA users (with existing releases of IPSA already featuring FALCON derived enhancements), but also allowed for FALCON specific implementations within the Wrapper (some of which required in their turn enabling facilities to be implemented in the kernel NMT system).

4.4.1 Core IPSA Developments

A number of key core developments were required within IPSA to implement fully the FALCON NMT, as summarised below:

4.4.1.1 Load and Generator Profiles

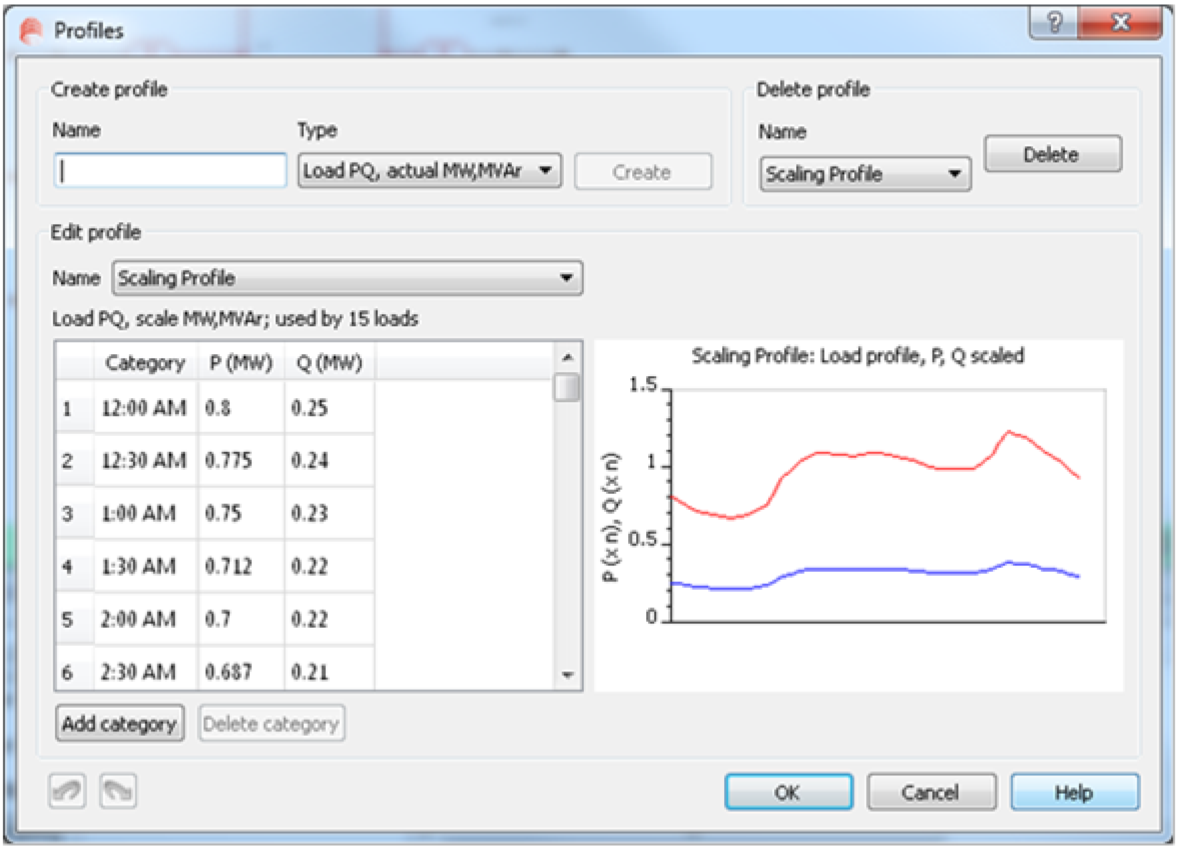
The inclusion of user definable load and generator profiles was an important addition to the core IPSA software tool. These profiles allow time of day analysis to be undertaken on a network. Each load and generator in the network can have different real and reactive power values specified thereby representing the real life dynamic loads and power flows on the system. The time resolution is also user specified allowing any time period to be analysed at any resolution.

Each profile is defined by a set of categories and associated real and reactive power values. There may be any number of time categories for a profile. Each profile can be used to scale an existing load or generator output or overwrite it during the load flow analysis. Any profile can be assigned to any load and a profile can be assigned to multiple loads. The time categories are arbitrary and represented by unique strings.

The profile data can be saved with the IPSA network model file but in the case of FALCON it is loaded into IPSA via the Python interface during the analysis. This reduced the file size of the network but required that the data was saved in a separate file. Future IPSA developments may allow large profile datasets to be stored in a database with the IPSA application reading the individual database tables as required.

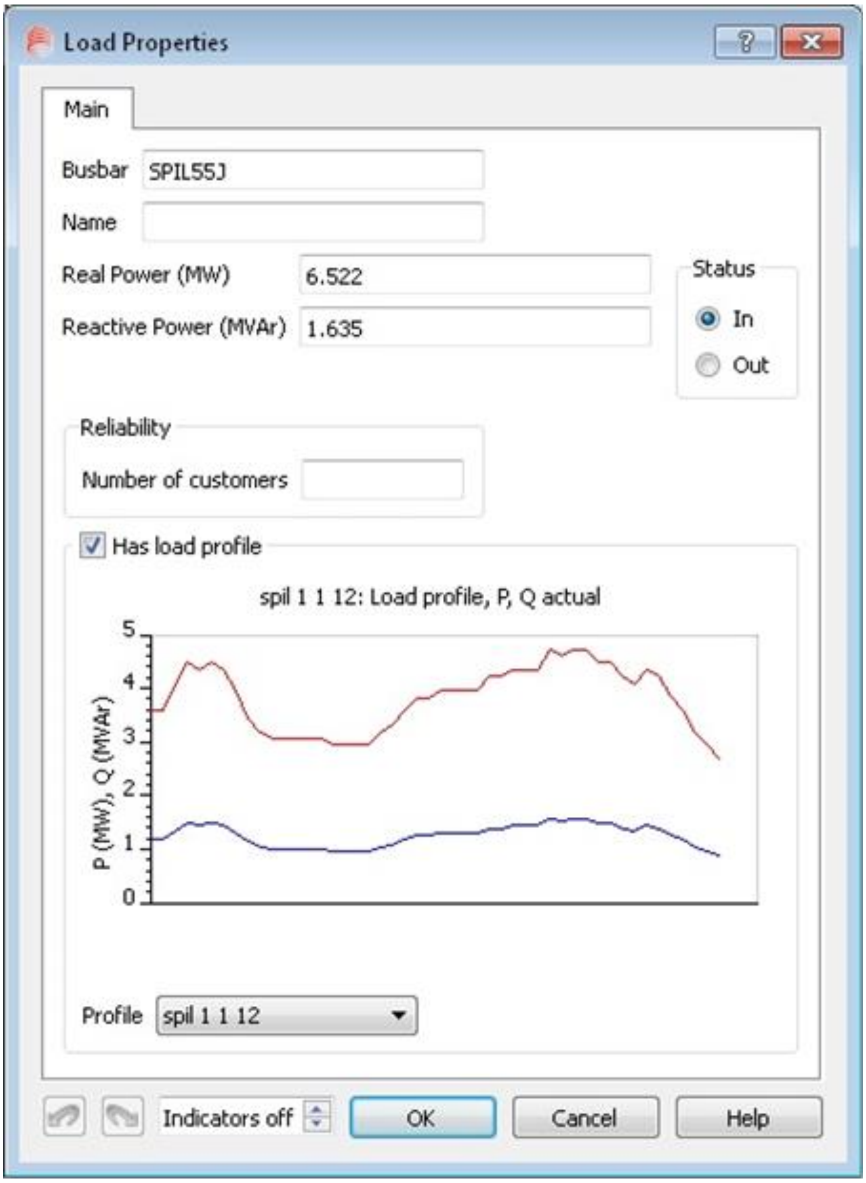
As well as being used to represent time varying demand and generation this feature was also used to represent the DG, DSM and Energy Storage techniques. The following screen shots show the IPSA dialogs to configure individual profiles and to assign those profiles to loads.

Figure 9: Load and Generator Profiles in IPSA - Load Profile Configuration Dialog



Source: TNEI/IPSA

Figure 10: IPSA - Load Profile Assigned to a Load Component



Source: TNEI/IPSA

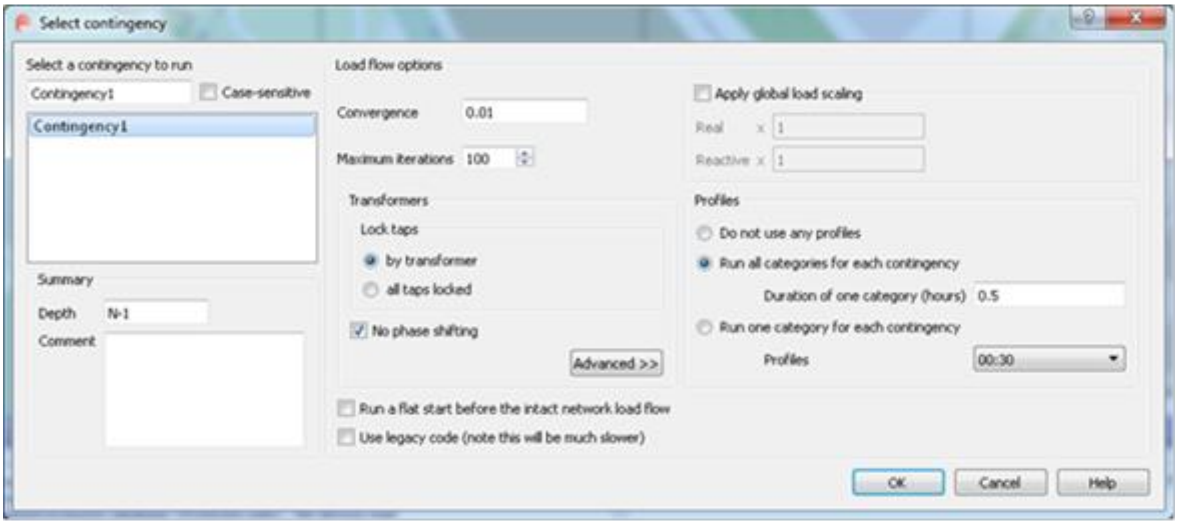
This feature has been used extensively for FALCON, the WPD Lincolnshire Low Carbon Hub LCNF project and other commercial projects by IPSA and its client userbase.

4.4.1.2 Profile Analysis

To support the analysis required by FALCON an additional function was added to the existing IPSA contingency analysis. The FALCON analysis required that 48 load flow calculations were undertaken for each characteristic day type, thereby calculating the power flows and voltages for every half hour in the specified day type. The results then had to be filtered to report only the thermal overloads and voltage exceptions.

The existing contingency analysis function in IPSA was capable of running multiple load flow calculations and reporting the exceptions for a single set of load and generation values. It was therefore decided to extend the contingency analysis feature to allow the use of the load and generation profiles. This would in effect report all network exceptions for all 48 half hours in the day. One of the principal advantages of this functionality is reducing the analysis time required. All load flow calculations and exception checking is undertaken by the core IPSA program which is significantly faster than performing individual load flow studies from the Python wrapper. The revised contingency analysis dialog is shown below with the FALCON additions outlined:

Figure 11: IPSA Contingency Selection



Source: TNEI/IPSA

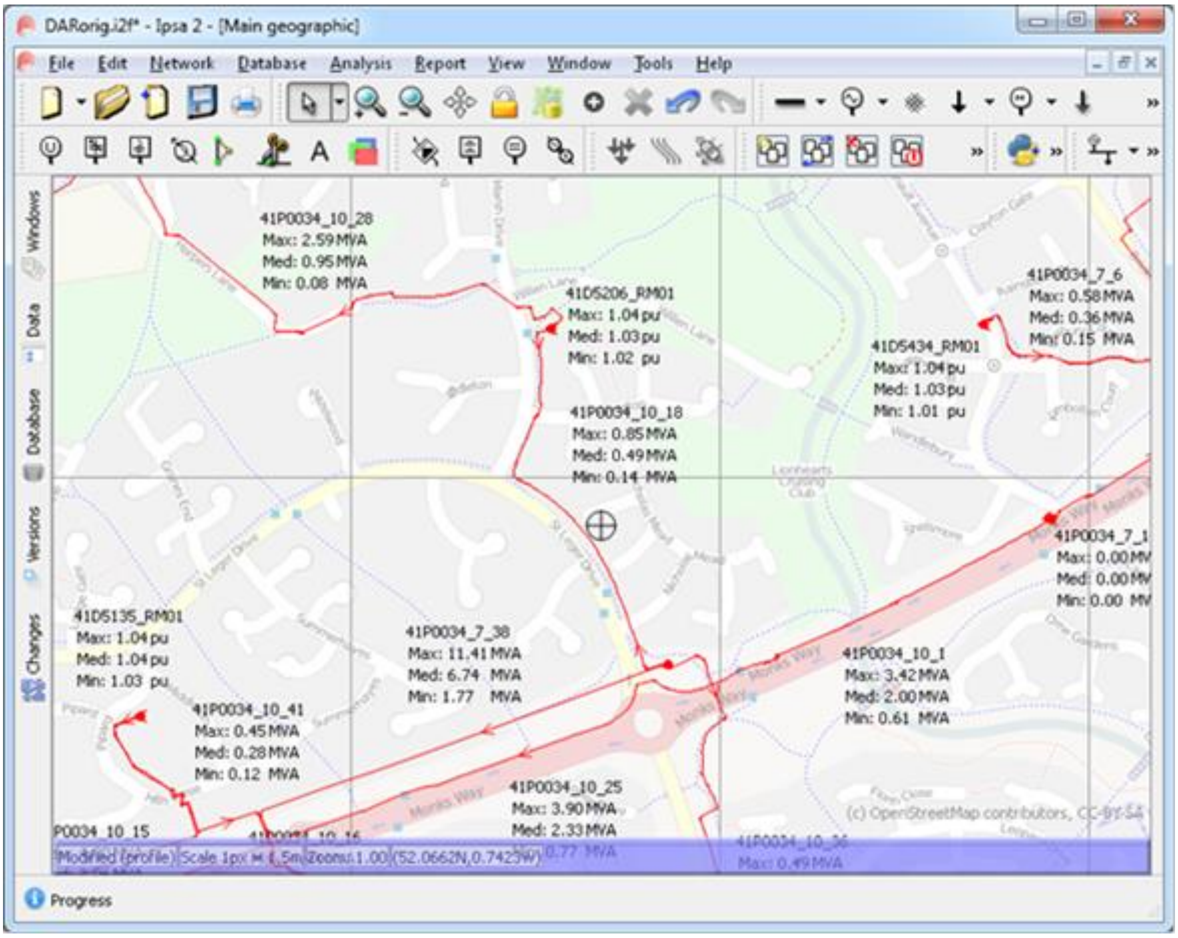
Two more analysis functions were also added to IPSA as a result of the profile functionality:

- Load flow calculations at a specific time of day;
- Profile analysis.

Individual load flow studies can be undertaken for any of the profile categories defined in the profiles. This allows results to be obtained for the loading condition at a particular time. It has also been used in the FALCON Wrapper by some of the technique applications.

The profile analysis runs load flow calculations for each set of time categories defined in the profiles displaying the results on the network diagram. These results indicate the minimum and maximum voltages and power flows for the load flows undertaken. Exception checking is also undertaken with appropriate diagram highlighting. The following screen shot demonstrates the display of a profile analysis on a typical day of data using the FALCON Master Network Model:

Figure 12: IPSA - Profile Analysis Display



Source: TNEI/IPSA

4.4.1.3 Version Control and Patches

Version control allows sets of network changes to be saved in the same file as the original network, in a similar way to the track changes feature in MS Word. Version control in IPSA records all changes to the power system data and diagram. The user can then edit a network and save the current network state as a new version. Changes can be made to any existing version and then saved as a new child version. A tree structure of network versions can be created.

This feature has been requested by IPSA clients for some time and the FALCON project has facilitated the implementation of this feature within the core product. It is most applicable to DNOs who maintain a single master network model with an accompanying set of proposed, planned and authorised changes.

The implementation of version control within IPSA was a complex task which took the software developers approximately one man year of effort to implement. The underlying technique recorded all user actions that resulted in a data or diagrammatic change, thereby enabling them to be reversed or reapplied as necessary. This proved to be more complex than originally envisaged since virtually all user operations had to be successfully integrated with the version control code. The resolution of bugs within the version control impacted on the development of the Python analysis wrapper and the wider SIM. Typical problems found are listed as follows:

- Certain changes were not originally included in version control. This resulted in valid changes being omitted from the difference files;
- Bugs were identified in opening or merging files if the version control data had not been correctly saved in the network files;
- Changes to certain components were not correctly handled and resulted in program crashes when creating the difference files.

An alternative method of version control was considered initially but rejected based on past experience. This method performed a network comparison only when required instead of maintaining a set of all changes made to the network. The complexity of the changes being made to the network may have resulted in this approach being more successful.

The facilities provided by version control enabled the FALCON techniques to be applied to the electrical network programmatically by the IPSA Wrapper. Version control functions then allowed the generation of a 'difference' file or patch (in FALCON terminology) which contained the differences between any two versions in the network. This difference file includes all component changes as well as new or deleted components.

The difference file can then be merged back into a different network as required. Merging is performed on the basis of identifying matching busbars, these are electrical connection points which IPSA uses as unique reference points. Any matching components would be updated whilst other components added or deleted from the original network as required.

The IPSA Wrapper produces a number of patch files whenever it is requested to apply a particular technique to resolve a failed asset. The Wrapper then makes suitable network changes programmatically before creating a patch file representing that particular technique. Some techniques such as DAR may produce just one patch file whilst others, for example ALT, many produce any number. These patch files are returned to the SIM for further analysis.

The difference and merge features of version control were integral to the operation of the Wrapper and the SIM.

The development of version control lead directly to the implementation of the undo and redo feature commonly found in software products which it was anticipated would become a user requirement if not supplied initially. The undo redo feature relies heavily on version control since it needs to step forward and back through the network changes that the user is making. This feature has long been a popular user request and was added to release version 2.5.1 of IPSA.

4.4.1.4 Profile Plugins

The FALCON project required the modelling of a number of techniques which included a time dependant element. Two methods existed in IPSA to allow these techniques to be modelled;

- Custom load or generation profile
  - This simply required the generation of additional load or generation profiles to represent the effects of the technique. These profiles were then saved with the technique patch itself and loaded back into the network as required.
- Hard coded plugin model
  - Plugin models are added to a single network component in IPSA. They are typically used for the analysis of fast transients so are normally used to represent generator governor and voltage regulators.
  - They are written in C++ and must be interfaced correctly with the core IPSA analysis.
  - They are provided to all IPSA users in the form of self-contained programs called DLLs which are installed with IPSA
  - A plugin model must be developed specifically for each type of analysis, for example load flow and transient stability.
  - The user is allowed to view and edit the parameters of the model but cannot change the fundamental operation.
  - Plugin models are very flexible and can be used to represent complex behaviour the is normally outside the scope of normal network component modelling

The time dependant techniques were modelled as follows;

Technique	Method
Dynamic cable rating	Plugin Model
Dynamic transformer rating	Plugin Model
Battery storage output	Custom Profile
Battery storage life	Plugin Model
Demand side management	Custom Profile
Distributed generation	Custom Profile
Alternate load transfer	Custom Profile

The plugin models developed for FALCON had the new requirement that they should work with the new profile analysis. This meant that they needed to operate in a similar way to conventional transient stability models, but instead interfaced with the IPSA load flow calculation. New functionality was added to core IPSA to allow these plugin models to be added to loads and generators enabling them to respond correctly or the results of the load flow analysis.

The plugin model interface required that the load flow calculation provided the results of the last load flow to the plugin model in order that the model can perform its calculations. The plugin models are therefore called after each load flow is complete. The plugin can then access the load flow calculation results and obtain the power flow results for the component that it is related to. The plugin can store results and internal variables between load flow calculations and can therefore fulfil the requirements of the various FALCON techniques. The plugin can then set internal IPSA flags to indicate if the component it is related to is overloaded or not.

This technique allowed the plugin models to be used with the IPSA profile analysis. Effectively the plugin model is run after completion of every one of the 48 half hourly load flows undertaken for each day type. This functionality is unique to IPSA and has been used on other projects already.

The plugin models to developed for FALCON included the dynamic asset rating models for cables and transformers. These required that the results of the load flow analysis were passed into the DAR model (developed by Aston University) in order to determine a time and current dependant rating for the individual asset.

4.4.1.5 Reliability Analysis

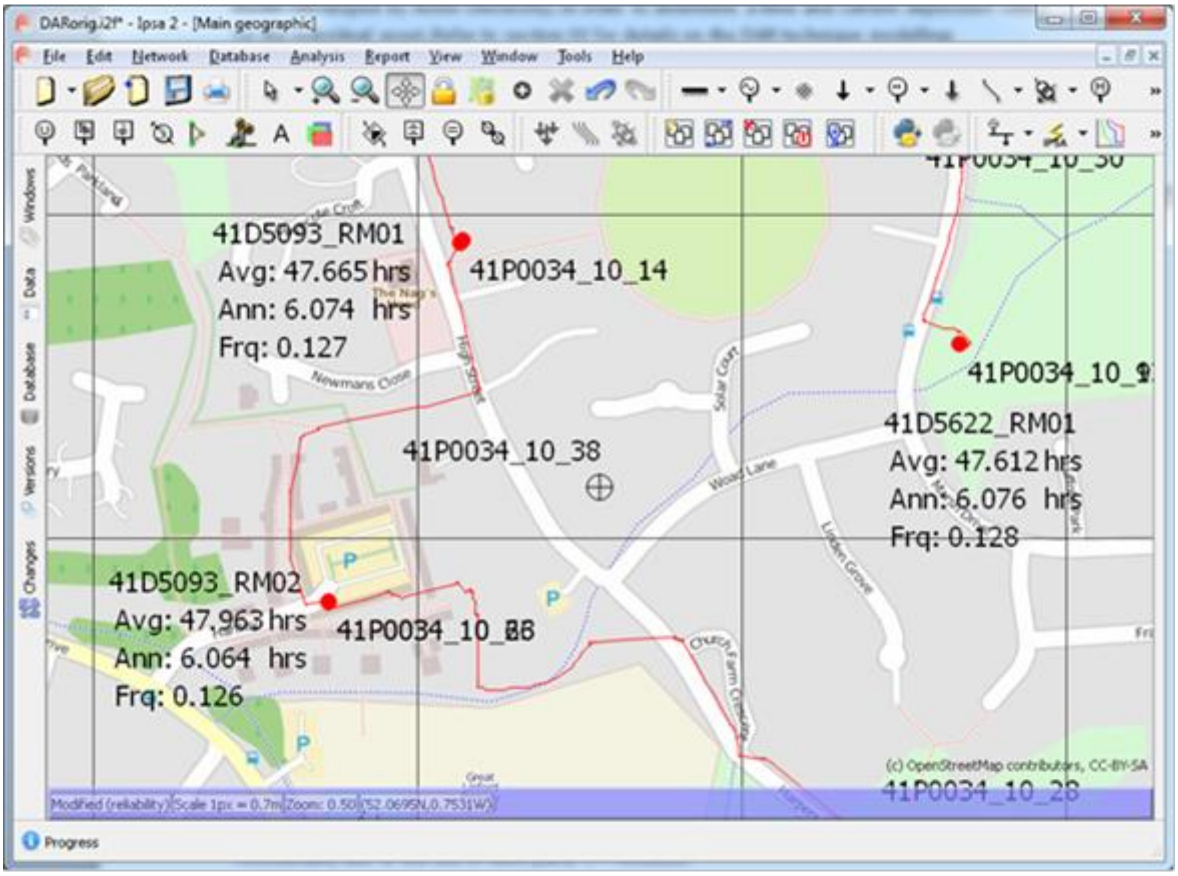
The FALCON project required that the network results metrics included the CIs and CMLs in order that the impact of the techniques on the network reliability could be ascertained. As IPSA did not include a reliability analysis tool TNEI were offered the use of software code developed specifically for IPSA as part of a university PhD project.

The majority of work to integrate this reliability code inside IPSA involved changing the various dialogs and filing mechanisms in order that the users could view, edit and save network reliability values. The code integration was more straightforward due to the modular nature of the IPSA software.

During this integration process it was determined that this analysis code was not suitable for a number of reasons. These included the code readability and the requirement that the analysis was suitable for analysing meshed networks. TNEI therefore decided to develop a reliability analysis calculation from the ground up. This development work took under three weeks and was simplified considerably due to the use of third party C++ modules.

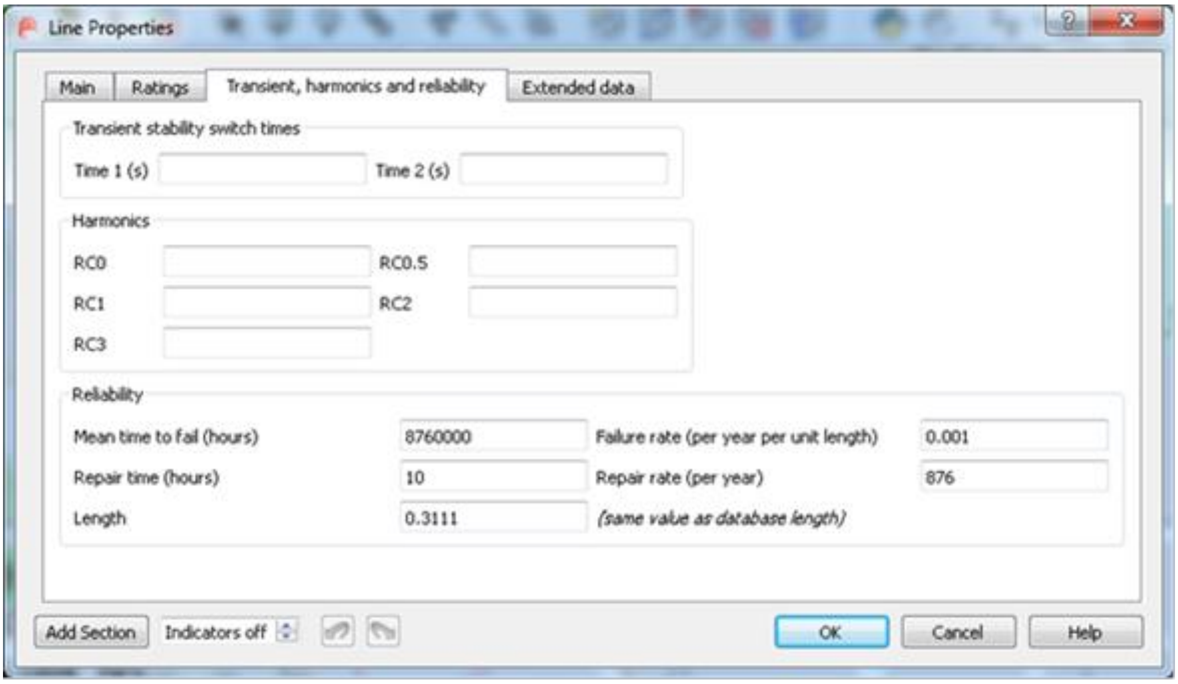
The following screenshots demonstrate some of the input data and results displays for the reliability analysis:

Figure 13: IPSA Reliability Analysis



Source: TNEI/IPSA

Figure 14: IPSA Reliability Analysis



Source: TNEI/IPSA

4.5 Development of the IPSA Wrapper

The additional functionality needed for FALCON required that an interface layer of code, known as the wrapper, be developed to provide the FALCON specific functionality. The decision to develop a separate wrapper as opposed to adding the functionality to the core IPSA product was based on the following considerations:

- Shorter development time required for the Python based Wrapper script;
- Large parts of the wrapper functionality would be specific to the FALCON project. Adding this to the core IPSA product would have added significantly complexity to IPSA which would have affected the operation of large parts of the code and interface;
- A Python interface would still have been required to interface with the SIM, to load networks and provide some level of control over the IPSA analysis.

The wrapper was therefore responsible for the following functions;

- Loading the power system network into IPSA;
- Loading the profile data into IPSA;
- Launching the load flow, fault level and reliability analysis in IPSA;
- Analysing the power system results and generating failures for the SIM;
- Generating patches for the various techniques as requested by the SIM;
- Merging patches back into the power system network;

- Launching the IPSA Software for use as a Data Manager, Network Editor or Results Viewer.

In order to facilitate the above some additional Python functions were added to the IPSA interface. This allowed the wrapper to programmatically undertake the actions required to complete the SIM functionality.

The wrapper interface with the SIM itself comprised a number of functions which were defined at an early stage of development. These were defined by the operation of the SIM search and, in approximate order or execution, are:

Function Name	Description
listApplicableTechniques	Indicates which of the FALCON techniques are complete
findAssetGroups	Generates a tree structure to allow the SIM to determine which assets belong to a particular asset group
analysePowerFlow	Performs the half hourly load flow analysis for each day type and returns all network failures
generatePatches	Generates a set of patches which may be used to resolve or alleviate a failed asset
fastAnalysePowerFlow	Performs the half hourly load flow analysis to determine if a particular patch resolves the failure on a failed asset
analyseIntactNetwork	Undertakes losses, fault and reliability analysis on the intact network and returns the results as state metrics to the SIM
runNetworkDataManager	Launches the IPSA software to allow the user selection for a set of primary substations
runEditor	Launches the IPSA software to allow the user to edit the network and create manual patches
runResultViewer	Launches the IPSA software to allow the user to view the results of the SIM analysis

The following sections summarise the key developments, challenges and lessons learnt during the wrapper development.

4.5.1.1 SIM and Wrapper Interface

The interface was originally specified at a high level only. A number of issues were encountered during integration due to different interpretations and were typically resolved quickly. To meet a number of new requirements which emerged during integration and validation testing, a number of additional changes to the interface were implemented immediately before final simulation runs were due to commence. These included changes to the data types being passed and the addition of new return data. The changes were required to fulfil some of the SIM requirements such as assigning results to a specific part of the network and were considered necessary in order to obtain a valid result set.

The level of detail and the control of changes for any critical interfaces is an important aspect of any software project. In the case of FALCON more focus on the interface and the management of it would have enabled a more efficient testing and validation to be undertaken in time for the final production runs of the SIM.

Some of the changes were implemented as a result of the testing to better reflect normal engineering judgement. These included:

- Not reporting out of limits voltage conditions on the low voltage (415V) networks. Voltage limits were changed from +/-10% to +/-6% in order to accurately capture all 11kV issues. 415V issues were not of interest to the SIM;
- Due to the method of importing the network data from geographic systems, there were a considerable number of cables with a very short length. These typically represented busbar connections or jumpers on overhead lines. These short cables introduced network failures which, due to their length, were very cheap to rectify. The SIM therefore initially picked these solutions for application across the remainder of the network. In some cases the length had been rounded down and where this became zero resulted in fee network reinforcements. To counter this, following expert engineering review of the SIM results during validation testing the wrapper code was changed to reflect the use of a minimum cable length.

4.5.1.2 Testing

One important aspect was the repeatability of the results and a significant amount of testing was undertaken to ensure that the analysis results were accurate. Testing was undertaken by both Cranfield University and TNEI in parallel. TNEI tested only the wrapper and IPSA functionality to remove the possibility that errors in SIM affected the analysis undertaken by the wrapper. Cranfield University were responsible for the integration testing of both the SIM and the wrapper.

Testing started by using simple test networks which could be used to demonstrate particular techniques or types of analysis. These networks were tailored to produce expected results and were therefore not fully representative of actual networks. They were principally used to test individual techniques.

The testing progressed onto using networks comprising a single feeder and a full primary extracted from the full Authorised Network Model. The use of real world networks introduced real world challenges. Load profile data had to be created for the test networks since this was not available from the Energy Model at the time. For Network editing was then required in order to generate the correct failures required for testing the wrapper. Networks were generally found to either generate no issues or many issues which was not ideal in terms of debug testing. This resulted in a limited set of test cases being developed for the standalone wrapper.

The method of loading the energy model profile data into the wrapper required the SIM itself, therefore wrapper testing with real data could only be undertaken by Cranfield. This resulted in only Cranfield being able to undertake the real world testing. Any issues had to be posted on the source control web site (Bit Bucket) together with sufficient source data to enable the test to be repeated using the wrapper alone. This made bug resolution slightly more complicated and less efficient than it could have been but was to the benefit of the integration and test activity overall.

One issue that became apparent during the simulation runs which used the Authorised Network Model was that earlier testing using the simpler networks was insufficient to fully test the wrapper and the techniques.

Some complex issues were identified which were only identified after extensive testing of the full SIM. These occurred at various stages of the full 35 year simulations under specific conditions such as the application of certain techniques. This resulted in failures which could not be resolved by any technique patches, or failing to produce patches for a particular failure.

4.5.1.3 Execution Speed

As the SIM was intended to be a prototype the main design consideration was robustness. The wrapper was therefore not optimised for execution speed and this resulted in extended simulation times. A number of elements contributed to the overall execution time, some of which were resolved during the course of the project;

Core IPSA Analysis Time

This is the time required by the core IPSA application to perform its functions.

The load flow analysis time is a function of the network size and is typically very fast. For a network of the size used by FALCON a single load flow calculation would be expected to take under 200milliseconds. When the 48 half hour periods and 18 day types are included this rises to over 3 minutes. This excludes the time taken for any operations by the wrapper itself. The extensive search space of the SIM therefore requires considerable analysis time when each node in the search requires minutes of execution time.

Speed improvements were identified and made in the core IPSA software to reduce the analysis time. A small number of issues related to the version control were identified and rectified which provided significant improvements. These were related to the way differences between networks were identified and saved in the patch files. In some cases differences were saved for the entire graphically data set in the network as opposed to just the components whose graphics had changed.

The dynamic cable rating model was also found to require excessive execution time due to its method of operation. This issue was resolved by reducing the accuracy of the rating model.

Wrapper Execution Time

The IPSA Wrapper was coded in Python as this language is supported by IPSA and by the SIM itself. Python code can run several times slower than compiled C++ code and therefore it is preferable to embed time consuming functions into core IPSA itself. Due to the bespoke nature of the SIM, the more complex functionality was undertaken by the wrapper, such as creating the technique patches and controlling the various analysis studies.

Detailed timing tests were not undertaken on the wrapper itself in order to reduce execution times. The wrapper itself took significantly less time than core IPSA, the areas where improvements could be made are as follows:

- Patch loading and merging;
  - The loading, validation and merging of individual patch files into the analysis network could be improved. Large numbers of patches in the later years of analysis took several tens of seconds to process;
- Improvements could be made by performing a review of the code and undertaking profiling tests to identify areas where execution could be optimised further.

The handling of the load profiles by the wrapper was changed in order to reduce the time taken to load profiles from the SIM into IPSA.

No other optimisation was undertaken on the wrapper itself although there are areas where performance improvements could be made;

- Patch generation
  - The SIM relies on the use of patch files which contain all differences required in order to implement a particular technique.
  - This requires that the technique is first modelled in IPSA then the differences identified and saved as a file. This file must then be read back into IPSA at a later stage.
  - An alternative method would be to simply record high level details of the patch without making network changes. The SIM then normally calls a specific function to test if a patch is effective, at this point the patch would be read to change the network as required. If effective the same high level data would be passed back to the SIM as a valid patch
  - The storage of high level patch data would reduce the amount of data to be transferred back to SIM significantly. It would not add significant time to the analysis since the changes specified by a patch need to be merged into a network by reading a file in, as opposed to programmatically editing the network.
- Transfer time consuming wrapper functions into core IPSA
  - A customised version of core IPSA could be developed which included certain key wrapper functions. Embedding these functions in the wrapper would reduce the execution time considerably due to the relative speed of compiled C++ over Python. For example, loading of profile data may be faster if core IPSA read the data directly from a database as opposed to passing it in through a set of scripted functions.

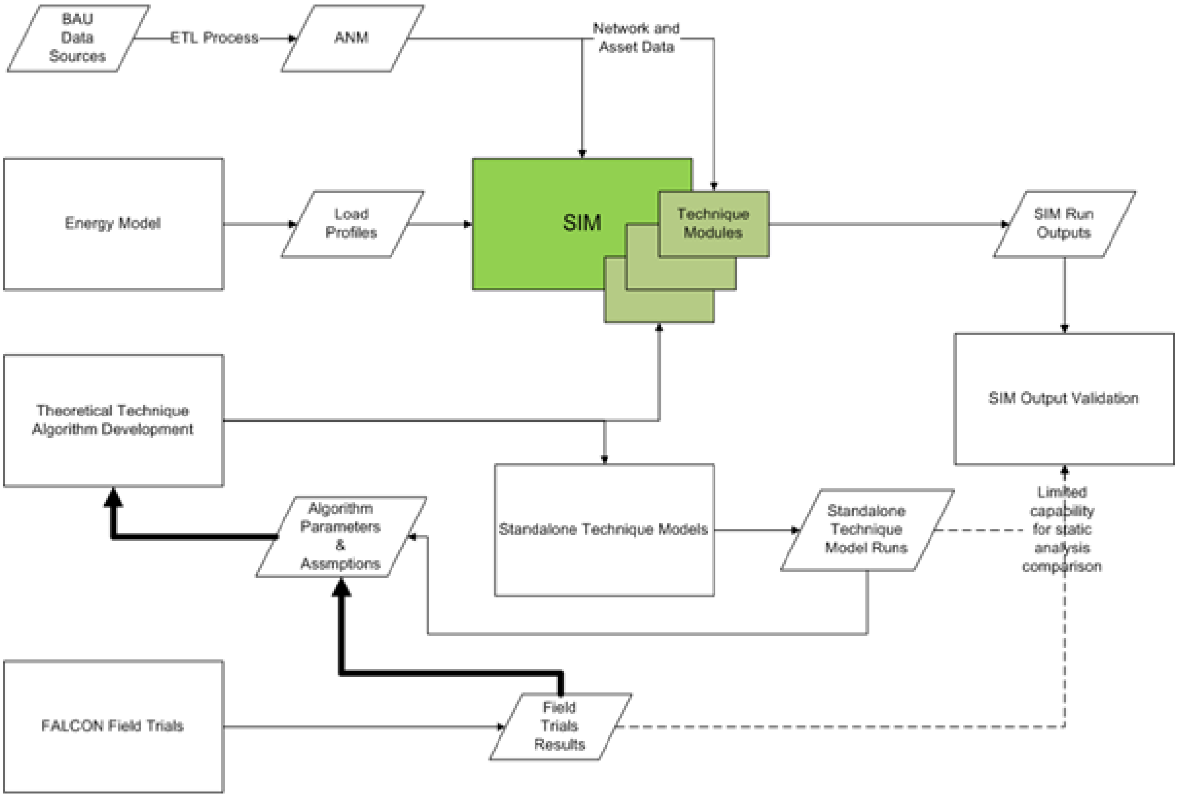
- The generation of technique patches could be optimised by converting the techniques to become built-in core IPSA components. Instead of writing a bespoke technique application to create a battery for example, a battery component in IPSA could be created. Such an IPSA component could contain the control logic needed to configure itself and respond automatically to network voltages and power flows, effectively producing an optimised output regardless of the network.

- Reduce the search area
  - A significant reduction may be obtained by performing load flow analysis only at the critical times of network loading. The conventional approach to network analysis relies on analysing the network at one particular half hour in the year, effectively looking at the worst case scenario for the full year. The recent trend in 'Smart Networks' encourages network designers to take account of individual demand and generation patterns as opposed to designing for the absolute worst case. This approach requires a significant amount of analysis as is evident in the overall SIM execution times. Undertaking analysis for the worst 5% of time when issues occur may further improve analysis speeds.

4.6 Linkage to FALCON Trials

The overall SIM context within FALCON is illustrated in the diagram below. The trials were always intended to inform and improve the accuracy of the SIM and the means of feedback and assimilation of the learning generated from the trials is indicated by the thick black arrow below. Essentially, the SIM techniques implementations are tuned using both general information gathered from and parameter values determined by operating the trials.

Figure 15: SIM - Trials Linkage



Source: FALCON Project

During the analysis conducted to meet the objectives of SDRC 5 in December 2014 it became necessary to draw attention to how some aspects of the project in relation to SIM/Trials linkage had been developed from the initial foreseen and documented intentions captured at the start of work.

The objective of SDRC 5 was to document the trials and validate the technique algorithms implemented in the SIM under a range of varying environmental and load conditions. Attention was specifically focussed on the principal factors which drive the accuracy of the technique models built into the SIM. Consideration of these points and bringing together the SIM and trials workstreams in this way, and at this time, would ensure maximum accuracy in the implemented algorithms along with recognition of any limitations and accompanying assumptions derived from insufficient modelling capability available at that point. This approach naturally also pointed the way to future trials and evaluations which might be proposed so as to support the development of even more accurate modelling algorithms for the future, and has indeed done so.

The SIM is a multi-year multi-objective search engine which can plan and respond to network evolutions out to a time horizon of 2050, while the trials are a single network snapshot being taken at a point in time (in this case during the trials phase in 2014/2015). The trials are thus a short-timescale view of very specific and small-scale areas of the network where trials equipment happens to be deployed. Essentially highly localised trials conducted over a short 18 month period at the start of a potentially 35 year long modelling interval are of no direct use themselves to the SIM modelling process, especially with a large network area under consideration.

Overall then, the technique modelling was the main area where the FALCON field trials fed back into the SIM workstream to enhance the end result. As a result, a number of improvements were made in the implementation of the technique models that had been initially included in the SIM based on theoretical algorithms. The SIM techniques were designed as code plug-ins to be used by IPSA when attempting to fix detected network constraints as the SIM experiment Runs progressed. As a result the SIM technique code was readily able to be updated to reflect new understanding coming from both the trials and the SIM workstream itself. (see SDRC 7 Report).

- Adjustments to certain parameterised values, to adopt a new (better) value;
- Adjustments to the representation of ambient environmental temperature to move this from being a single fixed value to an array of values to reflect diurnal variations flagged as significant to the overall computational accuracy of DAR techniques.

The actual list of improvements was obtained from the engineering and commercial techniques implementation teams and turned into a table of candidate changes. These were assessed for impact in terms of scope for improvement set against difficulty or timescale of implementation and a priority list then derived for the pilot SIM. The remaining enhancements not taken up for the prototype SIM have been flagged for later inclusion in a later SIM version. The following table presents the feedback items from the trials and describes what was done to accommodate each point by adjustment of the modelling approach.

Learning Point	Recommendation arising from Trials	Action Taken in SIM Techniques
Cable DAR Learning points		
LP 91	It is recommended that cable types within the Authorised Network Model are reviewed to confirm that all required cable types are now included in the available SIM technique code.	WPD Reviewed and found need for 3 cable models covering 95% of possible MK cases. Implemented by TNEI as additional models and deployed. 15 different cable types implemented plus a default set of parameters.
LP 97	Review the availability of cable construction details (as shown in Table 5) for all the cable types present in the FALCON Trials Area Authorised Network Model.	Cable types modelled include metric and imperial sizes, aluminium and copper conductors, XLPE, PILCSWA and PICAS
LP 92	Implicit assumptions with the SIM implementation about starting environmental and cable temperatures require review to confirm that valid cable external surface temperatures are being	New Aston DAR code implemented to correctly initialise the core temperature based on the initial starting current.

Learning Point	Recommendation arising from Trials	Action Taken in SIM Techniques
	generated from the first half-hour period of SIM analysis. Potentially bigger issue – if the daily variation of the cable temperature is less than 1 oC because of thermal lag, then modelling single days in the SIM is complicated because the pre-start temperature becomes the day's temperature. Effort is needed to assess the pre-start temperature and define how many days' worth of analysis is required to allow the temperatures to stabilise sufficiently over a day's load cycle to be representative of the system within the SIM.	
LP 95	It is currently recommended that a soil thermal diffusivity is established by interpolation. However, given learning point 94 above, the soil diffusivity becomes fixed at 5.76x10-7m2·s−1.	New value implemented as a default value for all DAR applications
LP 96	It is currently recommended five profile season values are used for soil temperature. However only data from April to November has thus far been obtained. Recommended values are: High Summer (July, August, September) : 20oC, Summer (June) : 18oC, Spring/Autumn (April, May, October) : 15oC, Winter months – to be determined – awaiting end of winter period.	Different ambient temperatures implemented as hard coded values for each day type in the analysis wrapper
LP 100	It is recommended that the SIM implements a maximum design operating temperature of 90^{0}C for polymeric insulation and 65^{o}C for oil impregnated cable or where rating is unknown. 75^{0}C as a limit for other paper cable can be used if this rating is confirmed by either the manufacturer or from data sheets.	Correctly rated cable temperatures implemented in the individual cable types modelled.
Secondary Transformer DAR Learning Points		
LP 102	Implicit assumptions with the SIM implementation about starting environmental and transformer temperatures require review to confirm that valid hot-spot temperatures are being generated from the first half-hour period of SIM analysis.	Modelling checked and verified as correct, no changes were necessary.
LP 103	Ambient temperature must be entered as an array of values for the day	Ambient temperature profiles based on day type have been implemented in the IPSA wrapper.
LP 104	Recommend that ambient temperature of the secondary transformer be: the prevailing modelled air temperature for the model day for outdoor substations; and: an elevated value for indoor substations. Further work will be undertaken to specify this elevated "offset" value. The Authorised Network Model should be used to	Ambient temperature profiles based on day type have been modelled with a 10degC reduction for indoor transformers applied.

Learning Point	Recommendation arising from Trials	Action Taken in SIM Techniques
	determine if the transformer is outdoor or indoor.	
LP 106	Due to demonstrated diversity in key parameter values, and current lack of correlation between parameter values and available Authorised Network Model transformer characteristics, it is recommended that conservative parameter values are used (DT_{tor}=55°C) and and t_o=180min for all secondary transformers. These are the example values from the standard, and will result in over-estimation of top oil temperatures. These estimates will however raise flags earlier with increasing transformer, and are therefore appropriately conservative in the context of the SIM. It is not viewed as reasonably practicable to undertake bespoke measurement and model parameter value tuning for each type of transformer (which appears to vary by manufacturer, by manufacture year, and by capacity).	New values entered in the default DAR parameter settings
LP 107	Hot spot temp validation is not possible within the scope of the trials and the wider FALCON Project for secondary transformers, as verification of actual hot-spot temperatures requires sophisticated factory installed measurement equipment fitted at the time of manufacture. Therefore all the hot spot modelled results for secondary transformers are based on example parameters from the standards. DThsr – hot-spot to top oil temperature rise at rated load is set as 23°C for FALCON modelling. In addition, the related time constant is also taken for example values in the standard. tw - winding time constant is set as 4 minutes for FALCON modelling.	New values entered in the default DAR parameter settings.
LP 108	As there is no readily available data for load losses and no load losses for each transformer type, a look-up table of typical values has been generated, based on transformer rating. The appropriate value of R for an individual transformer can be estimated with this resource. It is recommended that this look-up table be implemented in the SIM. No significant data is currently available about the influence of tap position. This is thought to be negligible in relation to the use of generic data and is therefore ignored within this modelling.	Losses are accounted for in both the DAR calculation and the normal IPSA power flow analysis.
LP 109	It is recommended that the SIM implements a maximum design operating temperature of 98°C for secondary transformers in the absence of other data from the Authorised Network Model.	New values were entered in the default DAR parameter settings.

Learning Point	Recommendation arising from Trials	Action Taken in SIM Techniques
	It is recommended that issue of life expiration of transformers, once DAR based operation occurs in practise, is further examined in the SIM, given the extended time periods potentially involved (modelling out to 2050).	

The trials themselves, the results and conclusions derived from them, and the implications of these conclusions for the SIM are documented extensively in a number of reference documents and FALCON end reports.

4.7 Technique Modelling in SIM

Modelling techniques with dynamic elements prompted modelling at half hourly resolution. So, for example, it would not be possible to determine the impact of charging and discharging batteries unless the network could be modelled over successive time periods, rather than at a single network peak condition. Similarly, Demand Side Management (DSM) was considered as a solution that would be best suited to network issues which occurred infrequently over the course of a year. This necessitated modelling not only within a day, but to use representative day types to understand the network issues over the course of a year.

SIM technique implementation was achieved by coding plug-in software modules, effectively as part of IPSA, which implemented the specified algorithms. The algorithms themselves were investigated and documented by academic institution (Aston University) and TNEI working for WPD. It is worth noting that the field trials of the techniques and the SIM implementation of the same are both explored by the FALCON project overall and that while substantially the same, they are subtly different.

As the techniques are implemented as software modules by design, it is therefore always possible to add additional techniques beyond those which were initially selected. This would necessarily involve further development of the Network Modelling Tool, which while outside the current scope of the SIM design can still be readily supported. The SIM design facilitates possible future addition of new techniques in the following ways:

- The technique models are located in a separate software module with clearly defined interfaces between the module and the rest of the SIM;
- The SIM provides a way to expose generic datasets to its internal search module and thus to the technique models. This enables implementation of techniques that require additional data that is not currently available within the SIM;
- The output of a technique is generalised in the form of a network patch which then feeds back into the SIM.

In this way a modular design, with generic interface support capability, was built in from the start and we thus consider the SIM to be open to future enhancement.

It is possible to turn techniques off if they are not applicable – the techniques to be deployed on a given SIM Run (Experiment) are selected in the Experiment Planner,

As noted above in the Section on the DAR technique, the project reasoned that there was nothing to be gained by the SIM modelling and including in its analysis overhead cable DAR.

The project considered a number of aspects and options concerning the modelling of the intervention techniques. These are discussed below.

4.7.1 Traditional Reinforcement

Traditional reinforcement is the term used for the set of conventional network management options and can be considered to have the capability to resolve network issues. Traditional reinforcement techniques are modelled within the SIM in the same way as the innovative techniques and are encoded as plug-ins that create patches to alter the network and to report associated costs.

Much of traditional reinforcement involves replacing a constrained asset with one or more of a higher rating, or introducing new assets to share load, such as a new feeder or a new substation. Not all the possible options that could be applied in real life were included in the SIM. One example is that the SIM does not directly mimic the process of creating a new 11kV substation as the process of determining a location can involve acquisition of land, wayleaves etc. which is uncertain and complex. For clarity, the SIM can include new substations via manual patches, but it does not suggest new substations as part of an automatic process. The SIM is limited to the 11kV network and so cannot mimic traditional reinforcement on other networks such as the addition of a new primary substation or changes to the LV network.

A small set of algorithms were used to represent traditional reinforcement and the rule bases used by the algorithms were simplified and do not capture all the decision making abilities of an experienced planner. This was an acceptable trade-off for FALCON but there may be opportunities to extend the abilities of algorithm based planning by including a wider range of data.

While there is a very diverse range of equipment deployed on the network, the SIM is limited in what it proposes for deployment when carrying out a replacement or upgrade as part of a traditional reinforcement intervention and is constrained to choose from a relatively short list of assets. This reflects the range of cables, lines and transformers that are actually available to planners.

One salient point concerning the “technique” of traditional reinforcement is that the SIM acts to solve problems and apply fixes locally – it is thus stepwise not holistic. The local planner knows his network and can take an informed view while the SIM can only look at the immediate problem in front of it.

The Traditional Reinforcement technique reduces to 4 main operations which can be applied by the SIM:

- Provision of a new feeder and transfer of part of an overloaded feeder;
- Permanent transfer of part of an existing feeder to another via jointing (rather than switching under ALT);
- Replace/add transformer (upgrade);
- Replace/add circuit (upgrade).
- These activities were considered the easiest to model using algorithms but planners might be expected to apply more complex changes that take into account future network development at the same time such as relocating assets, adding additional protection stages, converting teed substations to looped in substations etc.

4.7.1.1 Transformers

The SIM technique holds a hardcoded transformer rating table to drive the NMT/IPSA decision making. Available replacements are identified based on the rating of the current transformer and, for thermal overloads, the magnitude of the overload.

After the largest transformer size has been used the SIM then assumes that a number of transformers can be installed. There is little information about the space available at ground mounted substations or the likelihood of being able to create a ground mounted substation near the site of an existing pole mounted transformer. This is another area where improvements in the input data would allow for more sophisticated algorithms to be applied. Without site specific information, the limit of additional transformers has been initially set to one for pole mounted sites and two for ground mounted sites. Not all ground mounted sites would be able to accommodate two additional transformers, but the limit has been set to reflect that the SIM is not modelling the addition of additional substations and so having a higher limit is a proxy for adding an additional substation.

The SIM may put in step changes over a number of years. The SIM can model both the minimum incremental upgrade and another upgrade that is initially oversized. The cost metrics will reflect which option provides better value for money when assessed over the evaluation timeframe. Initial oversizing may be better value than the cost of two incremental upgrades, or may make sense if the financial value of losses was set very high. This is covered by BaU policy.

It was identified during testing that the simple replacement table methodology did not accurately reflect the normal engineering approach. The operation to replace a transformer with two of the same rating assumed that the original transformer would be replaced. Refinements were included such that the original transformer was kept and one new transformer added. Instances of transformers being replaced by one of an identical rating were found and investigation revealed that this was due to the inconsistent use of cyclic and continuous ratings.

For each failed asset the wrapper generated a set of technique patches, one patch for each possible transformer upgrade option. The individual patches defined the changes required to the network in order to implement the patch.

No allowance for single phase transformers was made or for the height of poles when installing multiple transformers. It was also assumed that sufficient ground space was available at pole or ground substations, if additional transformers were installed. Additional switches were included when additional transformers were installed.

The range of transformers installed is broad so there is some mapping of transformers to a modern day equivalent to determine the starting point within the transformer replacement table. The table allows for upgrading from single phase to three phase transformers, from overhead to ground mounted transformer types. Additional transformers would incur costs for associated switchgear. Moving from pole mounted to ground mounted transformers includes the additional costs such as creating a new plinth etc. but could be improved in future to ensure a check is included in the algorithm for ferro-resonance and an overhead switch included as necessary.

The current version of the SIM does not have data for the height of the poles which would affect the options for installing additional transformers and switchgear. Providing enhanced data for a more sophisticated algorithm is a potential enhancement to the SIM for later versions.

4.7.1.2 Circuits

The replacement of cables, either overhead or underground, was performed in a similar manner to the transformer replacement. The wrapper held a hard-coded list of standard OHL and cable sizes and ratings which could then be selected as replacements.

Constraints were applied so that underground cables could not be replaced by overhead lines. Upgrading overhead lines required the original circuit to be removed and replaced by a new one. Underground cables were left in the ground and a second cable installed.

All circuit lengths were left unchanged, even if an OHL was replaced by a cable. Typically the cable would be routed in a road verge whilst the OHL would be routed more directly. No consideration was given to the upgraded installation requirements, e.g. extra cable ducting or larger poles.

Once again the full array of options available to a planner has been simplified such that overloaded overhead lines are replaced with conductor the next size up. Underground cables that are overloaded have additional cables laid and jointed in parallel. (The original algorithm disconnected the initially in place cable but this meant that in some cases two new cables were being installed rather than continuing to make use of the existing asset).

The algorithm scans for adjacent sections of line or cable that are near overload conditions and replaces longer lengths where this would be a more realistic option. It is assumed that where the capacity of overhead lines is exceeded it would be possible to install underground cables along the same route.

Generic costs for upgrades are given on a per km basis. The SIM is not calculating the details of the required work in terms of moving poles to account for different spans for overhead or redesigning the path of the conductor. There is scope to improve the costing of new cables as at present the cost to install two new cables is given as twice the cost of installing a single cable. This will overestimate costs as the incremental cost of an additional cable will be relatively low. However no representative cost could be found for installing two cables together and this is not expected to happen frequently within the SIM.

4.7.2 Dynamic Asset Rating

This technique seeks to utilise dynamic ratings of lines, transformers and cables, based on the real-time asset state (derived from preceding operating circumstances) and actual prevailing environmental factors, rather than using fixed ratings as is the operational paradigm in use today. Fixed ratings are calculated to ensure that assets are not damaged under reasonable assumptions for operating conditions. However often actual conditions are more favourable than the assumptions used to derive ratings. Thus, the assets can be driven harder to carry more current for longer periods at times when this is judged to be possible because the assets will not be degraded by doing so. Typically in the winter the environmental temperatures are lower but demand may be highest – this is when DAR benefits from positive prevailing (enabling) conditions and has most beneficial effect for the network. This is reflected to a certain degree in seasonal ratings for assets, however the Dynamic Asset Rating technique extends this further considering a wider range of typical days and modelling the expected load patterns at half hourly resolution.

There is a difference between using Dynamic Asset Ratings for operational or planning purposes. For real-time implementations the temperatures, wind speeds etc. can be monitored and used to determine ratings and there will be options available to ensure that if conditions change that excess current can be managed. For long term planning, we use average predicted weather variables with average predicted loads. This is used to determine whether Dynamic Asset Ratings are likely to provide additional headroom but is not a cast iron guarantee that real-time conditions will always be favourable. There will be some interdependence between the application of Dynamic Asset Rating and the availability of other mechanisms to handle excess current when required, such are re-arranging the network, use of batteries, demand side management or constraining generation. These interdependencies have not been modelled within the SIM but should be borne in mind when interpreting the results.

For the SIM, enabling a dynamic rating support capability means implementing an algorithmic model of the assets subject to DAR, although this is currently restricted to transformers (both primary and secondary) and cables (both overhead and underground were initially considered, the former being dropped during implementation from the SIM however for reasons that are described below). The models compute asset temperature as a function of load taking into account such factors as construction type and various associated parameters (insulation type and thickness, materials used in construction) and environmental factors like ambient air (or ground) temperature and the nature of the ground in which they are emplaced (for example - thermal diffusivity of soil). Different models are required for different types of cable and are in turn derived from alternative modelling methods. A number of limiting assumptions are present concerning the degree to which the overall asset system can be accurately modelled. These are described in the conclusions section below under Technique Modelling in SIM.

Project milestone SDRC5 described how trials of the techniques investigated aspects of DAR with a view to tuning the implementation of the same techniques in the SIM

The aspects investigated were

- Mathematical thermal models of the assets under passive operation, and actively loaded conditions for a range of daily, weekly and seasonal circumstances;
- Potential impacts (both benefits and constraints) that could be derived for altered operational approaches that utilise dynamic asset ratings;
- Opportunities for pre-emptive action to take advantage of DAR (e.g. pre-cooling of transformers).

One of the early decisions taken for the SIM was not to include overhead line DAR modelling within the SIM modelled capability set. This was because overhead lines have a very low thermal inertia - less than a few minutes, whereas cables and transformers have a much higher thermal inertia measured in terms of hours. This means that an overhead line carrying a load above the usual rating could reach critical temperature with a 30 minute period and the load profile before or after that period has little impact on whether an overload occurs. The dynamic asset rating for an overhead line reflects both wind speed and direction which can change rapidly and are not well represented by average half hourly values for representative day types. Where conservative estimates are given for these values, then the dynamic asset ratings calculated tend to offer no additional headroom than the seasonal ratings currently employed. This was a finding from the dynamic asset rating trials on overhead lines.

The DAR technique(s) proved to be very algorithmic and required significant new mathematical input to achieve a workable solution. The algorithms for DAR were provided by Aston University and were pre-coded by them using both Excel and MATLAB harnesses prior to being replicated in the SIM using Python as NMT plug-in modules. The SIM handling clearly has to relate to every asset evaluated as a DAR candidate during the SIM RUN (power flow and thermal analysis in the IPSA core) drawing upon specific asset details as supplied by (and limited by the capabilities of) the Authorised Network Model network database, and conducted at each half hourly datapoint on the diurnal load graph so as to evaluate the asset against the load at that point. Environmental information at the same datapoint also has to be taken into account. Most of the parameters in this area are not assumed to be time varying (soil thermal diffusivity etc.) however it was determined from the trials feedback that a non-static (diurnally varying) ambient environmental temperature was needed to give accurate results, rather than assuming a constant value, and this was built into the SIM in early 2015 as an enhancement to the prototype.

The project also considered how best to model the environment of the assets under DAR. A number of considerations readily become apparent when this starts to be looked at in detail. For example:

- For transformers inside a GRP or brick building, the ambient air temperature is NOT the temperature of the outside air, with the temperature inside the building generally being higher due to insulation maintaining heat generated by transformers, solar gain, etc., though still offset from the ambient air temperature of the location. The level of solar gain bears a direct relationship to the amount of sunlight falling on the enclosure which in turn is related to a number of factors, not all of which can themselves be readily modelled:
  - Surrounding tree cover and consequent shadowing of the enclosure;
  - Growth of trees even if the above had been modelled at some point;
  - Surrounding buildings and position of enclosure relative to these and consequent shadowing of the enclosure;
  - Potential for moving/parked vehicles to shade the enclosure;
  - Construction material used in and type of enclosure;
  - Level of cloud cover;
  - Wind speed and direction;
  - Time of year and time of day (the former feeding back to point (1) as it may affect the level of foliage present.
- A number of the above points also apply to outside transformers in an ground mounted open stockade enclosure or for pole mounted locations;
- For underground cables, similar factors are in play and include:
  - The nature of the burial including factors such as whether the cable is in ducting or laid directly in the soil, whether single phase cables are laid in trefoil or flat formation, and whether it is in close proximity to other cables. Any or all of these factors may vary considerably over the cable span;
  - The vertical and horizontal homogeneity of the soil type assumed for the burial;
  - The constancy of the burial depth;
  - The moisture content of the soil (itself a property having a distinct temporal variation);
  - The soil type predominating at the depth of burial of the cable affecting the ability of the ground to conduct away heat;
  - The ability of the Authorised Network Model to know in detail the cable types from the many which are available and to map these onto the modelling algorithms implemented in the SIM and used to evaluate the network (see below).

4.7.2.1 Cable Modelling

There was a realisation during the SDRC5 report preparation that the modelling approach was incomplete across the very diverse range of cables actually deployed in the ground and that their type and construction was a significant factor in how the SIM should model their thermal response. There is much more in depth discussion on this issue presented in the Trials Final Reports. In the end, however, the project deployed three thermal cable models (two more were developed during the project) such that the DAR capability could finally account for around 95% of the available cable types deployed on the FALCON trials network. To effect the necessary functionality in the SIM it was necessary to create a cross-reference mapping table of Authorised Network Model cable types to the three thermal models so that these could be called as required at Run time and also required a cable type categorisation analysis for real time thermal rating. The initial implementation had only one model covering all the cable types, implying that this aspect was too inaccurate without the expansion in the model types. This was a key learning point.

A further evolution in understanding of cable modelling for DAR followed from the implementation of the more complete algorithm model set. The theoretical modelling and MATLAB mockups pointed to a need to run an 80 day stabilisation for each model to allow the operating temperature to converge on an accurate operational value. When executed in the SIM however such an extended initialisation was prohibitively expensive in processing time and the project sought an optimisation method which could arrive at the same view of operational temperature without significant additional processing (via an informed rule-of-thumb).

During the SIM testing the convergence accuracy of the cable model was adjusted in order to reduce the time required to calculate the cable temperature profile. This lead to an expected error of approximately 3°C to 5°C below the actual cable conductor temperature, resulting in a slightly lower dynamic rating than would be achieved in reality.

The DAR techniques were implemented using an IPSA plugin model, C++ code, which was compiled into a DLL which in turn formed part of the core IPSA application. The interface between IPSA and the plugin model allowed the plugin to indicate dynamic overloads as IPSA progressed through each of the 48 half hours in each SIM day. The full DAR algorithm required that up to 80 iterations were required to accurately determine the operating temperature. This in turn meant that the DAR results could only be determined following the last half hour of analysis for each day type. Therefore any overloads would only be flagged up for the last half hour as opposed to any point during the day. Additional functionality was required to save the final results in the network model, post processing was then undertaken to extract these results and interpret them inside the wrapper itself.

The format of the results presented a minor complication since the DAR models calculated the temperature profile. This profile was dependant on the load profile as well as the shape of the profile. The algorithms did not generate a dynamic current or power rating, instead they only provided a temperature profile. Some additional work would be required in future to convert the temperature profile back to a power profile which would be more suited to overload reporting.

4.7.3 Automated Load Transfer

This technique uses existing (and optionally new) NOPs to mitigate network constraints by transferring load between a group of feeders in the same set of interconnected feeders. The load transfer is effected by closing an existing NOP and opening another switch to create a new a new NOP established at a different point on the feeder.

Terminology

The terminology "Normal" open point will have less meaning with the greater application of this technique as it could be that a feeder will have a varying set of open points during the day, each of which is only "Normal" for the particular time period.

It is assumed that all these circuit breakers and NOPs are, or can be, remotely controlled and therefore can be used in an automated scheme. By this method an overload on a particular feeder can potentially be removed by shifting the load onto an adjacent feeder having spare capacity.

The FALCON field trials covered two distinct trial areas of network, and were based on the prevailing network loads. The trials explored:

- Potential impacts, both benefits and trade-offs, that could be derived from implementing alternative network configurations (normal open points that are different to the pre-existing set);
- Various types of impact, including: feeder load balance; feeder utilisation; circuit losses; circuit voltages; and
- Potential to schedule changes to normal open points that deliver material net benefits.

Two forms of ALT were identified during the SIM design phase, these being: predetermined and optimised modes. Only the first was actually modelled in the SIM. This is because the optimised mode requires real-time data inputs that would deliver benefits in operation but can't be usefully modelled for long term planning.

The cost of adding automation (if and only if not already present) is factored into the SIM technique.

The ALT method may not provide significant benefits for thermally constrained networks. Most thermal constraints occur under N-1 conditions and therefore additional load transfer may either be insufficient to resolve the constraint, or may not be possible at all. Thermal constraints under normal operation may be resolved using ALT.

Voltage constraints may benefit from using ALT on the affected network. It is anticipated that the most onerous voltage constraints occur under intact network conditions as the system must operate within tighter voltage limits. The intact network voltage limits are taken as ±5% whilst under N-1 conditions the limits were originally set to ±10%.

The SIM was later configured to ignore voltage issues under N-1 conditions entirely due to the possibility of incurring unrealistic levels of investment that would not be justifiable

The application of an automated switching scheme to an N-1 network is not considered to be representative of the way a physical system would operate. It is expected that under transient fault conditions there would already be automatic switching operations which occur as a result of the interruption, such as auto-reclosers. The time which an N-1 condition is expected to be maintained is also short with restoration times of minutes or hours. Therefore the addition of ALT during a short term transient condition is not considered to be a realistic method of increasing network capacity.

ALT may therefore provide most benefit to the intact network under voltage constrained conditions. Therefore the ALT scheme will only be configured to operate under intact network conditions.

Initially the project analysis identified two operating modes which the scheme could implement. These were referred to as the 'Pre-Determined and 'Optimised' modes.

4.7.3.1 Pre-Determined Mode

ALT Pre-determined mode was implemented within the SIM. This operating configuration will apply an alternative switching configuration when a constraint is detected. Essentially the same switching sequence is applied to the intact network for each day type and diurnal period with a constraint.

The Pre-Determined mode operates only in response to a constraint which imposes the following characteristics:

- The scheme would operate during intact network conditions only
  - The alternate switching configuration is kept unchanged during N-1 operation
- The alternative switching configuration would be selected based on one of
  - Time of day operation
    - Fixed operating times for all day types and years
  - Voltage constrained
    - Operating times determined separately for each day type
  - Thermally constrained
    - Operating times determined separately for each day type
- The operation for two coincident constraints may be undefined
  - Two separate constraints may have two separate and conflicting switching operations defined
  - These multiple operations may result in a network which is either meshed or has an isolated section with no source of supply
  - Operation under this condition should be avoided by preventing the simultaneous operation of schemes on the same set of interconnected feeders

4.7.3.2 Optimised Mode

Optimised mode was dropped as the pre-determined mode in a wider SIM optimisation framework provides exactly the same benefits as the optimised mode. Specifically, the SIM search chooses the most suitable configuration of pre-determined mode while considering other automatic patches that apply to the network. As the optimised mode was first defined as a potential option, it is described here to provide a complete picture.

The optimised mode as defined would provide a less flexible approach to resolving network constraints. This method determines and adjusts the optimum switching configuration for each day of analysis, but does not consider other combinations of intervention techniques to resolve the issue. The exact switching configuration is therefore dynamic and independent of configurations used in other days or years.

The general operation of the scheme is as follows:

- Run a full day of intact load flow analysis and obtain constraint results
  - Identify network constraints for each period in the load profile
- Check if a scheme needs to operate in response to one of the identified network constraints then;
  - Determine possible alternative switching configurations
  - Determine asset group losses, CIs and CMLs for each configuration
  - Select the optimised switch configuration
  - Check if the number of switching operations has been exceeded and reduce if required
- Repeat the full day of intact and N-1 analysis
  - Apply the optimised switching scheme as previously determined

The scheme operates only in response to a constraint which imposes the following characteristics:

- The scheme would operate during intact network conditions only
  - The optimised switching configuration is unchanged during N-1 operation
- The operation for coincident constraints may not resolve all constraints
  - Multiple constraints may have separate and conflicting switching operations defined.
  - The switching optimisation search should identify the configuration with least onerous constraints

4.7.3.3 Design Considerations

The wrapper locates all switches on a feeder and any adjacent feeders. It then performs a series of load flow calculations to determine if any switching combinations are able to reduce or remove a particular overload. For each combination the normally open point is switched in (closed) and one other switch is opened to create a new open point. Any successful combinations are returned as a patch which defines the switching actions required.

The cost models generated for each patch take account of the type of switch and whether additional automation is required.

Merging an ALT patch into the network for analysis required that the switching operations were undertaken by the wrapper as opposed to being part of the network model data and undertaken by core IPSA. Future developments to improve ALT handling within the SIM could use the Network Controller model (which currently exists in IPSA) which could perform the required switching automatically.

ALT options depend on the nature of the switchgear present. Remote control is required to effect the switching and so a site must be located where either remote controlled switches are already installed or they can be installed. The algorithm assumes that where remote control is required this is achieved by a switchgear change rather than a retrofit upgrade to existing equipment. Additional information could be included within the Authorised Network Model to refine the application of the algorithm to reflect the ease of remote control upgrade at different locations combining factors such as the type of switchgear but also potentially factors such as signal strength for communications.

Additional automation to improve network performance would reduce the likely implementation costs of ALT and similarly increase automation for ALT would have positive impacts on network performance.

4.7.4 Meshed Networks

Within the SIM this technique is implemented by identifying the normally open points on the feeder being analysed. A set of patches are then produced which contain all combinations of the normally open points in a closed state. For example if a feeder included two normally open switches then 3 patches would be produced:

- Switch 1 closed and switch 2 open;
- Switch 2 closed and switch 1 open;
- Switch 1 closed and switch 2 closed.

These patches would then be passed back to the SIM and analysed individually. Circulating power flows are dealt with by the load flow analysis automatically and do not cause an issue for IPSA.

The meshed patch is applied to the normal system configuration, this then affects the network operation under N-1.

The FALCON field trials sought to operate the 11kV network with parallel feeding arrangements, with protective device driven auto-sectioning zones, so as to explore:

- potential impacts, both benefits and trade-offs, that could be derived from parallel feeder configurations;
- potential impact, both benefits and constraints, of operation with auto-sectioning zones (e.g. possible improvement in CIs and CMLs, balanced against time/effort & cost); and
- Specific protection arrangements needed to implement auto-sectioning zones, and their effectiveness.

Meshes are created by replacing the switch at a normal open point (or suitable switching point nearby) with a breaker and creating protection zones. In the event of a fault within the mesh this breaker will operate to return the feeders to radial operation. Therefore meshed networks have some limitations on their ability to resolve networks under N-1 conditions as the network may operate as radial feeders depending on the fault location.

4.7.5 Energy Storage

The wrapper implementation of Energy Storage comprised a search algorithm and a battery sizing algorithm.

The search algorithm identified up to four possible locations along the constrained feeder. These locations were, for simplicity, based on distance along the feeder from the primary substation. The wrapper created a solution for each combination of the four locations in order to generate a sufficient number of patches for the SIM.

For each set of battery locations a load flow calculation was performed to determine the minimum battery rating required to remove the network constraint. The minimum battery rating was then processed by the Aston battery sizing algorithm (from the original Project Technique specification) to determine correct battery based on a hard coded set of standard battery parameters. The Aston algorithm calculated the battery and converter losses as well as the charging requirements.

Following the selection of an appropriate battery size a charge/discharge profile was created for the battery. The charge profile was calculated such that the battery would be fully recharged during the same day if possible. In addition, the charge periods were chosen during the periods of lowest demand on the feeder. This gave an accurate representation of the battery power flow during a particular day type. Individual profiles are created for each day type where a network failure is being resolved.

The battery itself was represented as an ideal generator in IPSA with the charge/discharge profiles attached to it. Each solution identified by the wrapper was then as a separate patch by the wrapper and returned to the SIM Harness.

The FALCON field trials sought to operate a single 11kV feeder with battery/inverter units installed at five LV substation locations so as to explore:

- Baseline operation of the LV substations and HV feeder without operation of the energy storage units;
- Peak lopping and trough filling using demand forecasts;

- Voltage response;
- Frequency response;
- Impact on power quality;
- Impact on imbalance;
- Specific operational circumstances, for example, response to circuit fault/disturbance.

This would inform the overall battery placement and operational strategies as well as providing guidance for the SIM implementation of Energy Storage – a new capability to WPD.

Battery addition requires additional elements such as inverters. The additional required space can rarely be accommodated within an existing substation. Batteries are also connected at LV so may require the installation of an additional transformer to provide an LV connection point if an existing suitable transformer location cannot be found. The issue with battery placement is much more than, say, simply adding an extra single GRP – there are also door clearance, height, weight and noise considerations.

This means that in practice not all the options explored and proposed currently by the SIM would be used in practice. Further, the ES equipment used in the FALCON trials is unlikely to be the same as that which would be used operationally in the future. Users are also likely to want to decline a number of SIM proposed battery deployments. It may therefore be better to take a pragmatic approach and flag sites as battery compatible inside the Authorised Network Model and have the SIM only try to deploy ES to such compatible locations, rather than proposing all.

Additionally, batteries are likely to be used in a way where (like DSM for example) they do not provide “permanent” solutions. More probably (once more compact and simpler to place) they may be deployed as cost/time saving items given more permanent solutions pending.

Operations costs are not going to be the same as the trials costs as the units will almost certainly not be the same. Upgrade costs are dependent on what equipment is already installed and it is not fully understood at the moment what is likely to be required. The maintenance costs used within the SIM have been estimated based on manufacturers recommendations, but are high compared to other technical solutions and do not include changing cells. Maintenance activity would include changing filters and checking the special fire extinguishers. The cost model for battery operation includes a separate element for losses which reflects the size and usage pattern of the battery.

4.7.5.1 ES Technique Tuning in SIM

The ES technique was evolved during the SIM test and validation phase of the project as a result of seeing the initial way in which ES deployments worked within the SIM. Initially many tens of battery deployment interventions were seen in some Runs and it became clear (especially when considering the above discussion) that battery placement needed to be less general. Given the restrictions in the input data (also noted above) it was therefore decided to limit battery placement by the following means using mechanisms already available in the prototype SIM:

- Batteries would not be selected at any pole mount location (details of this location attribute already being present in the Authorised Network Model) – these sites would not be able to accommodate the necessary equipment;
- Batteries would be limited to a single 100kVA unit at any single location, corresponding to the size of units actually deployed to the field in the FALCON trials.
- Batteries are limited to five installations per feeder to reflect the likely difficulties in finding appropriate sites.

4.7.6 Demand Side Management (DSM)

The Demand Side Management technique in FALCON refers to customers reducing their demand by changing how they operate their business. This might also be termed demand side response (DSR) or load reduction (LR). Where a customer reduces their load by using their own generation, we have defined this as the DG technique which has many similarities with DSM but is considered separately within the SIM to allow customer potential to be specified for each technique.

The DSM and DG techniques have similar features, in that they both require the specification of available capacity and the way in which they are operated so that the revised load profile for a substation can be calculated. DG can be seen as a special case of DSM which has no impact on load before or after the load reduction period. Much of this section relates to both commercial techniques. The execution of field trials of the commercial techniques was carried out by FALCON between 2013 and 2015 in two phases and is covered in much more detail by FALCON Commercial Trials Final Report.

The essential concept is the identification of an avoidance event and the shifting of load away from the peak usually to an acceptable pre or post event interval or to supplement the site with its own generation capability. The trials had been intended to establish, and where possible quantify, the behaviour that takes place in a DSR event, however key findings from FALCON are that the sample size in the trials that were actually carried out was not sufficiently large to quantify the load turndown and/or the pre/post event adjustment increases to be able to inform the SIM implementation.

There remain considerable unknowns around DSM and DG. DG is expensive and if used regularly might become more expensive than traditional reinforcement. Reliability of DG is also an issue, as demonstrated during (S1) FALCON trials, so that (S2) trials were designed to move from on-demand to pre-planned use of DSR (seeking a reliability improvement) and in such cases the SIM might be able to help with planning. At the present time DSM does not have CAPEX, only OPEX cost elements.

The SIM models N-1 operating modes in addition to the intact operating modes of the network. It is very likely that most of the detected issues will occur in N-1 modes, i.e., the probability to actually see them in real operating conditions is very low. For example, the

SIM might detect a total of 50 hours of overloads on a particular asset in a year, all in different N-1 modes. Addressing the issue using battery storage or traditional reinforcement would incur significant costs for an event which will happen infrequently and may be restored quickly and thus provide poor value for money. Using the commercial techniques, however, would very likely have a low operating cost, and could potentially be zero if not used (assuming that contracts are place without availability fees or retainer payments. This represents far better value for money, so long as sufficient capacity can be contracted with a high enough certainty of response when required.

Estimating capacity is difficult for a number of reasons. Firstly, the FALCON DDR trials customer base was small enough that that it is not possible to draw conclusions about average capacity for different types of customer. While the Energy Model splits load into different end use types so that those end uses which are simpler to shift can be identified, the majority of the trials participants switched to their own DG in which case the capacity is dictated by their generator and not their load profile.

Secondly, the difficultly of contacting customers at a specific location e.g. a particular HV feeder, was not tested during the trial that encouraged participants from the wider Milton Keynes area.

Thirdly, customer willingness and capacity to participate in DG/DSM is unlikely to remain constant for the long timescales used in SIM planning. The normal economic cycle of businesses changing, growing or closing makes it unlikely that the same values can be used in 2015 and 2050. Similarly, as the market for demand side services evolves there is no way to predict how much of the potential capacity may prefer to contract with other parties, even if commercial barriers to sharing services are removed.

These factors suggested that a very low proportion of the available capacity should be assumed. The derivation of the customer attributes are covered in the next section.

A useful addition to the SIM would be a module that is able to estimate the amount of controllable[2] DSM and DG capacity present in the network based on what is connected to a given substation. DG records are available in Crown and could be added to the data extracted for the Authorised Network Model.

A certain degree of flexibility is being encouraged with the adoption of Active Network Management where customers accept reduced export capacity at critical times as a trade-off for lower cost connections which can be achieved faster. Establishing flexibility at the time of connection seems more likely to be successful than recruiting DSM/DG customers who have a less certain benefit.

In terms of trials results informing SIM Technique “parameters” for the Commercial Techniques 5&6, the 2013/14 trials series used an inappropriate data capture device which did not permit the sort of analysis of local meter to substation mapping that would

[2] PV is technically DG but no use for DSR planning.

be needed to calibrate the SIM technique. New Squirrel devices were therefore used for the 2014/15 series trials.

Other input from trials back to SIM mainly informed how best to use it, and still evolving models for costing the commercial aspects that remain limited by conflict with other DSR services being purchased by National Grid. Costs currently looking like a “pay per use” model with no up front (DNO) investment cost but there will be a necessity to establish the total cost of recruitment, setup fees and potentially other items.

When Demand Reduction is requested for period, depending on the type that is being offered to be reduced, the project analysis determined that there may be:

- An increase in the customer demand (from its normal demand) in the time periods immediately before the requested period (if it is a pre-scheduled request); and
- An increase in the customer demand (from the normal demand) in the time periods immediately after the requested period in order to recover any postponed processes.

This is natural and reflects preparatory and recovery activities such as pre and post cooling (for refrigeration for example). The pre-increase, reduction and post increase amounts are based upon a percentage of the demands in the respective periods. In this way it is possible to model different types of demand response, for example:

- Setting the Pre and Post increase percentage to zero would model the response as a reduction in the demand during the period with no increase before or after the response period;
- Setting the Post increase percentage to zero would model the response as a reduction in the demand during the period with an increase before but no increase after the response period; setting the pre-increase percentage to zero would model the response as a reduction in the demand during the period with no increase before but an increase after the response period.

Note: An alternative method would be to set the pre-Increase period to zero instead of setting the pre-increase kW to zero and similarly for the post increase period and kW.

In practice, the FALCON field trials were unable to gather the necessary quantitative information required to correctly gauge the pre/post event levels. This has been covered in several other areas of the report, and there are various factors relating to why insufficient load reduction participants could be identified. One of those suggested from (S1) was that due to the typically smaller capacity of DSR that can be offered by reduction sites versus that generation makes the financial incentive insufficient. The (S2) trial therefore tested this sensitivity by doubling the payment for load reduction sites and confirmed the inclusion of SIM capability to vary the incentive levels between techniques.

4.7.6.1 DSM Controlling Parameters

As noted in the previous section, one of the key findings of the actual trials is that identification, recruitment and operation of demand reduction is at this time unlikely. Despite two years of opportunity being presented to the whole of the UK demand response service provider they were unable to bring any to the trials despite the broad geography offered to them, although one was directly contracted. It is therefore statistically unlikely that suitable sites can be found exactly where they would be needed in order to employ DSR as a standard technique to manage 11kV constraints. Thus, the trials effectively stresses that the current arrangements are not sufficiently attractive to customers, but in spite of this it is still valuable to include Load Reduction in the SIM to assess the outcomes which arise. However the approach taken is to only include half hourly metered customers as possibly being interested and to set take-up values as quite low. While there is less certainty that the SIM should rely on commercial techniques to provide resolution of specific network issues, it is possible to do some sensitivity analysis to predict the impact of different levels of availability or to reflect different payment values.

Capacity Assessment – End Use Types

The technique originally assumed that in each half hourly load value there would be a split by end use. This became unwieldy so it was suggested to add a split by category and time of day that could be applied to the values from the energy model within IPSA. To support this it was necessary to categorise all the substations in the Authorised Network Model and provide a mechanism by which these could be passed to IPSA.

Parameter Validation

Data from trials is only available to provide input validation for distributed generation. It is possible to look in greater depth at the generator functions / type and fuel source if this is of any value or concern. The only FALCON commercial trials data available for load reduction is the industrial load from a single water processing site. This is an insufficient base from which to draw any meaningful conclusions.

For demand reduction by end use the implementation used a parameterised DSR function to specify what percentage of each load type might be reduced under DSR and required this value to also incorporate an estimate of reliability. So, for example, if the substation has 100kW of refrigeration load and we set the demand reduction factor for refrigeration at 30% then it assumes that it is possible to reduce refrigeration load by 30kW.

This demand reduction factor percentage value has to reflect:

1. What proportion of load relates to I&C customers (if we are considering I&C DSR only);
2. What proportion of load customers can technically shift;
3. What proportion of customers would contract to shift load, and;
4. What proportion of customers would shift load when required – i.e. reliability.

Values for case 1 could be derived, the proportion of load that is I&C customers, for each substation. This is for each substation and means further detail to pass from Authorised Network Model to IPSA. Based on results rather than assumptions we would have to conclude the volume of available load reduction is zero from substations.

However values for 2 and 3 were considered to be difficult to obtain – an area that perhaps requires further investigation. Adequate customer data is not available to identify whether it was a lack of technical capability or insufficient interest that prevented them providing service.

To be able to proceed, for technical shift capability 2, the assumption of 50% for each type of load was made. For 3, the proportion that would sign up to a contract, given the lack of willingness to sign up for DSR, we assumed application of a very low value here, but if this had been set to zero then we would have been unable to model DG either. The project did not have details of where customers have their own standby generation so it was not possible to increase the factor for those customers only.

It was possible to obtain a view of the split of load between half hourly and non-half hourly metered I&C customers. The question then is: If we were to put a likelihood value on it, what would be reasonable assumption for participation rates if the price is "reasonably attractive". Values of 5% of customers in profile class 5-8 and 10% of half hourly metered customers seemed to provide a reasonable starting assumption.

An estimate of reliability for point 4 derived from FALCON trials and others indicated 75% as a reasonable starting assumption. It is critical that separation of the two commercial technique methods (DSM/DG) is maintained as it would be misleading to present generator results for load reductions.

Other Parameters

- The code was initially set for half hour of pre-demand reduction activity, followed by half an hour of demand reduction and another half an hour of post demand reduction recovery. It seemed to be a fair position to take that we would be more likely to contract for more than half an hour of demand response – perhaps two to two and a half hours. The forecasting method has confirmed that really we need to contract for a minimum of 90 minutes to around 180 minutes although the majority of events will be manageable with two hour event window. It should be noted that generation does not require any recovery as the site should not have a rebound effect resulting in a rise above the expected returning load;
- For completeness, it was assumed that there were no more than 15 applications of DSM per site per year with no more than 30 hours a year max duration. Again this is a point available for validation from the trials - which tend to indicate that if DSR is recommended for use it will be where it is not being used for 50 or even 20 hours per annum for 11kV. If it is very occasional under planned N-1 conditions then it is going to probably give a huge financial benefit but once regular events are likely then it would be expected that capital investment would be the preference of the business.

Data would tend to suggest that we should use a metric of 20 events and 50 hours to be safe. This is the upper end of what would prove to be economically viable in any single year. However as this is 'pay as you go' it would not be expected for this to be required unless a worst case scenario year occurred where there was a prolonged cold spell or N-1 condition driving abnormal circumstances. If this was forecast to be a common annual requirement then it would be worthwhile revisiting capital funded options.

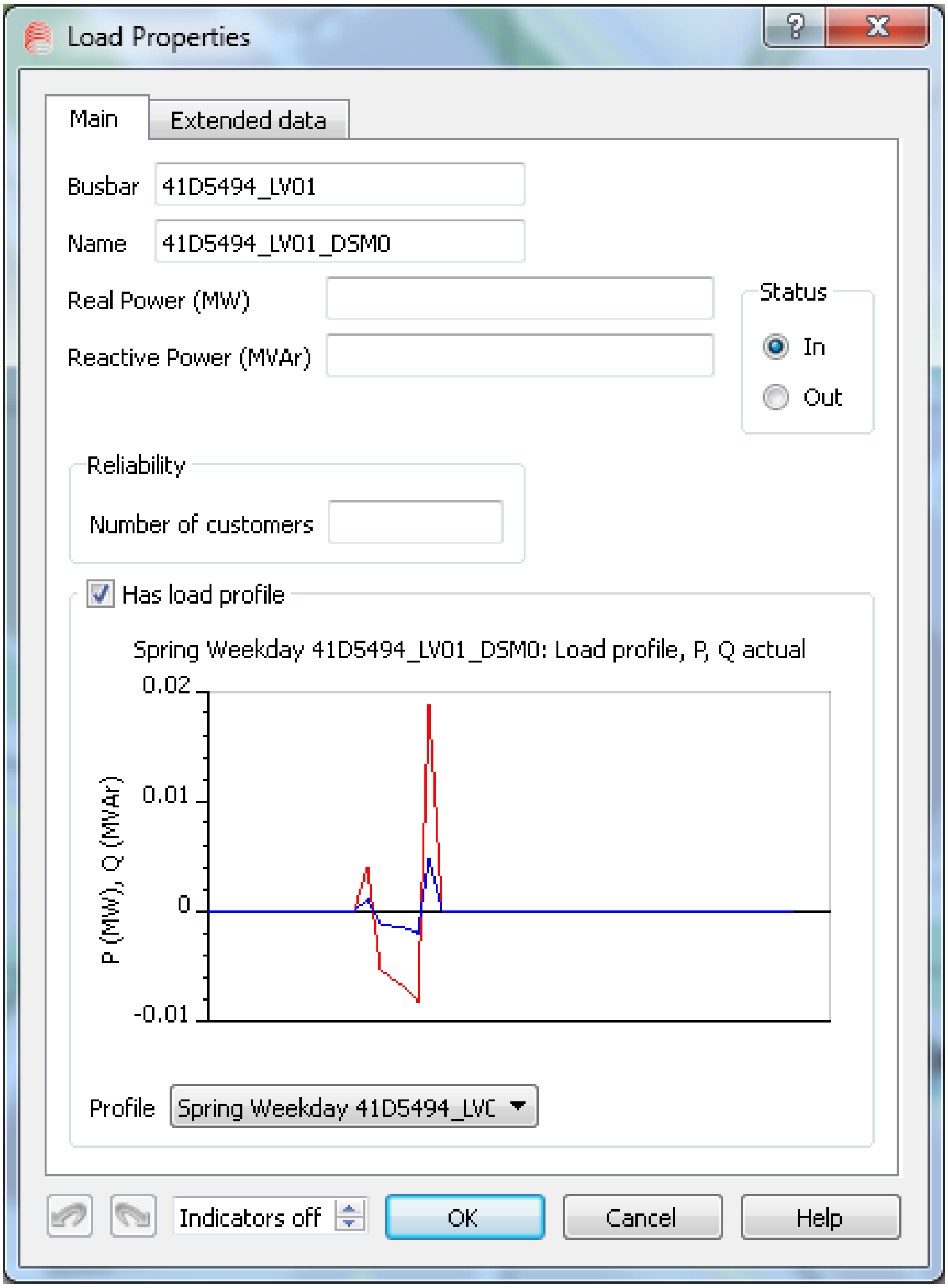
IPSA Implementation

Both the DSM and DG technique implementations differed from other techniques as additional non power system network data was required in order to create the necessary patches. Users are required to edit the various loads in the network model to indicate the amount of DSM and DG that is available at a particular low substation.

The implementation of the techniques was then straightforward. A search is performed to identify all substations with DSM or DG capability on the feeder with the failed asset. A set of load flow calculations is then performed to determine which combinations of identified DSM/DG substations resolve or reduce the overload on the failed asset. Combinations of substations which do not reduce the power flow through the failed asset are rejected.

For each successful combination, a new DSM load (or DG generator) is created in the network model. This allows the effect of DSM/DG to be represented by adding a load profile to the new component which represents the contribution of the individual customer. A load profile is then created for each DSM/DG load. Each profile therefore includes two positive loads representing the pre and post periods and one negative load representing the main reduction period. An example from one of the SIM runs is shown below:

Figure 16: Example DSM Profile



Source: TNEI/IPSA

The above profile models a DSM reduction of approximately 6kW to 8kW over a 2 hour period. This is preceded by a half hour 4kW pre-reduction period. There is then a final 18kW post reduction period. The red trace is the real power whilst the blue trace is the reactive power.

4.7.7 Demand Side Management - Distributed Generation (DG)

Following due consideration a separate technique specification for DG was not provided by the project and therefore the same underlying algorithmic model for the techniques was used for both DSM-LR and DSM-DG. For DG however a change was needed to reflect the fact that customers using DG would not have much by way of pre-demand reduction load increase (i.e. no freezer pre-cooling for example) or post-demand reduction load increase (e.g. no recovery from heating systems working harder). Having one single approach to the two techniques does however effectively mean that it is necessary to have a set of controlling parameters that work for both cases. This therefore adds certain complications as we might assume, say, that all refrigeration load could be reduced if we are switching to DG but only some of it if DSR is assumed.

Because of this approach, the two techniques are discussed in detail together – so the reader is referred to the section above on DSM.

For FALCON, none of the Distributed Generation trials resulted in an export of power onto the network, just a reduction in power imported from the network.

4.8 Search Methods and Exploring the Solution Search Space

This is a key function of the overall SIM implementation – essentially it presents a new capability to evaluate the network state through a vast number of evolutionary possibilities and follow these states as they are explored.

The SIM search always starts with an unevaluated network state in the first year of the experiment (initial network state). Following a power flow study, the *search* either moves on to the following year, or, if the network state has failures, saves it into failed network states store. The SIM proceeds by selecting a failed network state from the failed network states store and applying one of the smart intervention techniques, along with conventional reinforcement, to resolve failures. Depending on the outcome of *patching*, the SIM either saves a new failed network state or moves on to the following year until the network state fails again.

To select a failed network state from the failed network states store, the SIM uses one of three algorithms, depth first, width first and A*. The depth first algorithm always tries to reach the end year of experiment as fast as possible by selecting the last saved network state. The width first algorithm performs an exhaustive exploration of the search space by always selecting the first network state from the failed network states store . Both depth first and width first algorithms do not take costs of interventions into account when deciding which network state to expand next.

In contrast, the A* algorithm aims to find the least-cost path through the search space. As A* traverses the search space, it builds a tree of partial paths. The leaf nodes of this tree (failed network states) are stored in a priority queue that is ordered using a cost function, which combines a heuristic estimate of the path cost to reach the goal h(x) and the distance travelled from the initial node g(x). In particular, the cost function is:

$$f(x) = g(x) + h(x) \qquad 1$$

where g(x) is the total expenditure cost (TOTEX) incurred so far and h(x) is a heuristic estimate of TOTEX to reach the end of experiment. The algorithm removes the next network state in the priority queue to apply intervention techniques. The search stops when the queue is exhausted or a termination criterion, such as the number of evaluated network states, is satisfied.

Unlike path finding tasks in which A* search is typically used, network evolution is a challenging problem, for which calculation of g(x) and h(x) is not straightforward. Equation 2 defines g(x), for a network state x_i in year i,

$$g(x_i) = (c_i + o_i) + \sum_{j=1}^{i-1} (c_j + o_j + m_j) \qquad 2$$

where c_i is CAPEX in the current year, o_i is OPEX in the current year, and c_j, o_j and m_j are CAPEX, OPEX and metrics costs of ancestor network state in year j with no issues. The heuristic estimate of cost to reach the end year is given by Equation 3,

$$h(x_i) = (\bar{c}_{REM_i} + \bar{m}_i) + \sum_{k=i+1}^{n} (\bar{c}_k + \bar{o}_k + \bar{m}_k) \qquad 3$$

where $\bar{c}_{(i\ REM)}$ is average remaining CAPEX in this year, $\bar{m}_i$ is average metrics cost in this year, $\bar{c}_k$, $\bar{o}_k$ and $\bar{m}_k$ are average CAPEX, OPEX and metrics costs of descendant network state in year k with no issues and n is the end year of evaluation.

4.8.1 Estimation of Future Years Costs

Equation 3 requires knowing average CAPEX, OPEX and metrics costs of descendant network states, which might not be known in advance. This section details how the SIM estimates these costs.

4.8.1.1 CAPEX Estimation

The SIM ranks all network states according to the number of failing asset groups. Thus, a fully compliant network state has a rank 0 and a network state with 5 failing assets has a rank 5. For each year of the experiment, the SIM has a vector c_{AVG} of historical average CAPEX to increase a rank of a network state by 1. For a year that has no network states in the database, the vector has a single constant value of DEFAULT_YEARLY_CAPEX = 2000.0, but any suitably low value would work.

In reality, fixing a noncompliant network state in most cases costs well over *DEFAULT_YEARLY_CAPEX*, forcing the SIM to use a learning process to adjust the average estimated CAPEX for years that have expanded network states in the database. For each year with at least a single network state in the database, the SIM computes two vectors $\boldsymbol{c}'_{AVG}$ and $\boldsymbol{p}$. Vector $\boldsymbol{c}'_{AVG}$ is predicted average CAPEX to increase a rank of a network state. Vector $\boldsymbol{p}$ is learning pressure, which increases with the number of network states of each rank in the database. The learning pressure exponentially increases with the number of network states of a given rank, reaching its maximum after 7 network states are expanded. Referring to Equation 4,

$$p_i = min(0.8, 0.05 \cdot \boldsymbol{m_{i,k}}^{1.5}) \qquad 4$$

where m(i,k) is the number of network states of rank i in year k. At the end of each iteration, an updated historical average CAPEX vector is computed according to Equation 5

$$\boldsymbol{c}_{AVG} = \boldsymbol{c}_{AVG} + (\boldsymbol{c}'_{AVG} - \boldsymbol{c}_{AVG}) \circ \boldsymbol{p} \qquad 5$$

In turn, the average CAPEX cost for entire year is obtained using Equation 6

$$\bar{c} = \boldsymbol{c}^T_{AVG}\boldsymbol{j} \qquad 6$$

where j is a column vector of ones.

4.8.1.2 OPEX Estimation

Initially the SIM assumes no OPEX costs are incurred. As the expansion progresses, some patches start to incur OPEX costs. Unlike CAPEX, OPEX continues to be incurred in the following years after the patch has been applied. An average OPEX value for a year can be obtained using Equation 7

$$\bar{o} = \boldsymbol{j}^T\boldsymbol{o}_c(\boldsymbol{j}^T\boldsymbol{j})^{-1} \qquad 7$$

where j is a column vector of ones, and oc is an OPEX vector of compliant network states in that year.

4.8.1.3 Metrics Cost Estimation

Metric cost is estimated like the OPEX. Initially the SIM assumes no metric costs in a year. Once compliant networks states appear in a year, the metric cost for that year is updated according to Equation 8

$$\bar{m} = \boldsymbol{j}^T\boldsymbol{m}_c(\boldsymbol{j}^T\boldsymbol{j})^{-1} \qquad 8$$

where j is a column vector of ones, and mc is a vector of metric costs of compliant network states in that year.

4.8.2 Estimation of Remaining Expenditure in the Current Year

The average remaining CAPEX in the year a network state is in is calculated using the vector of historical average CAPEX cAVG and the network state's rank according to Equation 9

$$\bar{c}_{REM} = \sum_{i=0}^{r-1} \boldsymbol{c}_{AVG\,i} \qquad 9$$

where r is the rank of the network state.

4.8.3 Tuning the Heuristics Based Search

The A* search mechanism is a guided search mechanism which required some tuning to find the most effective implementation. This section looks at how this was done. Without tuning in this way the search can operate non optimally, resulting in overly long evaluations.

4.8.3.1 Ranking of Network States

Initially the SIM was using a single average CAPEX value for each year to predict future expansion costs. During verification Runs it was observed that the costs to fix an asset group could change by a factor of 1000 depending on the asset group type, which would make the estimation of remaining expenditure in a year very coarse and, consequently, result in a slow expansion. To address this issue it was decided to rank network states according to the number of asset groups with failures remaining and maintain a set of averages for each year and for each rank.

4.8.3.2 Using Fully Fixed Network States to Estimate Metrics Costs

The SIM calculates metrics costs from metrics data obtained as a result of a dedicated IPSA Wrapper utility which operates on the intact network. Consequently this cost can be directly calculated only for network states with no constraint violations. This presents a problem as the fixed network states and their descendants in following years are becoming more expensive because of metrics costs suddenly being added to them once the network states are fixed. This prevents the A* search from expanding descendants of fixed network states. The issue can be solved in two ways, namely, by not including metrics costs in the A* cost function or by making sure the metrics costs are correctly propagated to the ancestor network states once a fixed network state is found. The SIM adopted the latter approach by initially assuming the metrics costs for all years to be 0 and updating them with an actual average value once fixed network states appear in a given year.

4.8.3.3 Using Asset Groups as an Indicator of Progress

In the early versions A* was using the number of failures as an indicator of progress within a year. Statistical analysis of SIM expansion trees gathered from early SIM Runs has revealed that the costs to fix a network state with constraints are not correlated with the number of issues. Instead, the costs and the number of applied patches were strongly correlated with the number of asset groups with constraints. In consequence the latest A* search versions use the number of asset groups with failures as an intra-year progress indicator.

4.9 Result Visualisation

With so much information being generated by a SIM Run, result visualisation is an important issue. There are two aspects to this – visualisation of the results for the Expert User and also for the Strategic/Planner User. The former is a much more involved case as it includes the execution of validation of the whole SIM as well as in depth data mining, however such users require less direction. For the latter class of users the visualisation must be self-contained and self-evident, they do not have recourse to making direct access the database structures of the SIM to supplement the native facilities provided for the users.

Visualising the SIM Results

Here the term Result means a unique set of investments applied to a network in a given time frame that resolves network issues, i.e. a unique chain of Network States rather than the more general concept of results as any output from the SIM runs.

The essential concept in the area of result visualisation concerns the effective display of the progression of Network States that the SIM evaluates. The Network State is a key concept for the SIM and can be categorised as Constrained (meaning the network has one or more voltage or thermal issues) or Fixed (that any thermal or voltage issues for that year have been resolved by the application of Patches.

The overall network state relationship is well represented by a branching tree structure. The presentation to the different user types then concerns the means whereby this tree is presented to them and the sort of information that is rendered available to supplement this graphical tree based representation.

Visualisation of SIM results includes presentation of the network evolution tree structure and detailed inspection of individual network states. The former is accomplished by the Results Browser, which presents two synchronised views on the SIM results, this includes a table showing aggregate metrics for each of the results and a tree graph representing network evolution. This side-by-side view allows simultaneous quantitative (table) and qualitative (tree graph) assessment of results. The table supports search and sort functionality that reduces the number of displayed results and reorders the displayed records. The tree structure is adjusted accordingly, by folding branches that are filtered out from the table and adjusting its layout to match the order in which the results are displayed in the table. Likewise, it is possible to filter the results by clicking on graph nodes. Additional interaction modes allow selecting specific results and launching Results Viewer, which is a tool that can be used to inspect individual network states in detail using a network diagram.

4.9.1 Supplementary Result Visualisation (For Expert Users)

In addition to the Network State Viewer which was specified early in the project an additional SIM Inspector tool was created that produced a self-contained HTML page that visualised the tree structure but also incorporated extensive tabulated data for each Network State.

Colour has proved to be a useful tool for distinguishing between different aspects of the results, such as the type of Network State and the techniques which have been applied when moving between Network States.

A number of actual examples of RUN screens, results and analysis are presented in Section 6.2.

4.9.2 Report Generation (For Expert Users)

The results database can be interrogated by tools to generate custom reports. However the form of the results within the database adds some additional complexities.

Firstly there are data types which are specific to Python and therefore require handling in Python via scrips. Secondly many of the logical objects such as a Result do not exist in a form that can be directly queried by SQL, but rather require some recursive scripting to first create the object from database tables. At the same time, the SIM contains an extensive library of helper functions implemented in Python that simplify data manipulation and report generation.

Python scripts were generated that could provide a number of reports for a particular experiment, including outputs in Excel, Word, PDF and JSON formats. This was later extended so that reports could be generated for all experiments on a machine. While these tools were effective, adding further tools in the future will require additional expertise in both the structure of the database and python scripting.

4.10 User Interaction

4.10.1 Tuning the User Interface

The SIM workstream initially intended to run a series of ten RAD cycles after the core SIM development was completed. These RAD cycles would draw upon the experience of a number of users identified to assist with the development programme as part of a formal User Group. A series of meetings were held when the SIM was still in design and implementation and while the SIM user interface was not itself ready, was able to draw on the IPSA components as working examples. The RAD cycles were not all completed however due to time constraints after the main integration phase overran. Consequently there was only limited scope for user feedback from the full User Group during the prototype development.

The sort of user related considerations providing focus early in the development included:

- The best way to optimise the experiment runner so as to ensure getting sufficient results but not to spend too much time processing and to how keep the user informed regarding processing progress (see below);
- Result management and visualisation given the number of results to be expected;

- Symbology – meaning of colour and look and feel on the user interface.

4.10.2 Execution Progress Tracking

During one of the early User Group meetings, some of the Users showed concern that the SIM might take a long time to run through its processing and consequently they requested some sort of indication of progress when runs were being carried out. A progress bar similar to common windows style progress bar indications was suggested. Progress bars are appropriate where the size of task (such as copying a file of a known size) and the system operation is deterministic so that the progress indication is largely linear in progression and can be displayed as such.

In the case of a SIM RUN however, the two significant states that result from a RUN taking place are when the system finds the first result (which by virtue of the way the A* Search works is likely to be the best one) and then when the search space is exhausted. Anything past the first result simply gives the engineer more alternatives to look at and potentially utilise in his further analysis. The state when the search space is exhausted does not have any practical significance for the engineer since for any real problem the size of the search space, and consequently the number of results (and the amount of time to explore it all) is excessively large. In summary, the size of the task involved in completing a SIM Run is largely unknown, and cannot be anticipated in advance in order to calibrate a progress bar indication.

It was however proposed for the SIM to display an indication of cumulative Result count (states evaluated and formal result solutions derived) for each active Run, thus ensuring that the Engineer could know how many alternatives had been located up to that time and an indication of the number of Network States that had been created.
This was then altered to include an indication of when the last Network State was created as a long duration between Network States can indicate a problem with the SIM run.

What could not be done easily was to present some sort of view on how far through the processing (for example as a percentage completion) the SIM has reached at any given point. In practice the SIM Inspector tool can be used to inspect the progress of the SIM Run and to see the latest year to be evaluated, the degree to which the simulation is branching, the mix of techniques applied and whether the simulation is creating useful patches or has run out of viable options.

4.11 Cost Model Implementation

4.11.1 Populating the Specific Values in the Cost Model

Difficulties were encountered when trying to source reliable and definitive cost data from within the business for use by the SIM. While values were readily available for the traditional reinforcement intervention technique, this was to be expected since this is effectively the standard remedial “technique” used by the business right now. The other (new) techniques are not currently in operation on the network and hence it proved to be a non-trivial matter to obtain elemental costs which are fundamentally different from current operating methods as well as drawing in some cases on different equipment.

The cost related issues were thus quite different across the different techniques, perhaps not an obvious expectation at the outset of the project but certainly a clear conclusion emerging from the overall analysis. Take for example the DAR Technique where costs are principally concerned with the potential for “per-use” degradation which may occur if there is any loss of life resulting from driving the assets harder given prevailing conditions where this is possible. There are no CAPEX costs for DAR as the existing assets are already deployed and being managed by the BAU process. However in a more overdriven operating mode clearly improved monitoring could be considered of value[3] so OPEX may be higher (i.e. associated with an increased need for more frequent asset inspections). The difficulty here comes in trying to anticipate how future BaU processes would adapt to such requirements. The project flags such issues for future consideration and FALCON made basic assumptions for the production cost model for the inclusion of values covering this sort of effect.

On the other hand DSR costs can be managed in a number of ways and might involve in-house or outsourced management models. Again CAPEX is minimal or even zero and the costs are associated with DSM management contracts etc. For batteries CAPEX and OPEX costs are high and this technique does not suit all areas.

4.11.1.1 Cost Breakdowns

While the SIM Search function is driven solely by total cost, the actual contributing cost elements were broken down by formal RIGs allocation areas to allow for a more detailed inspection of the cost factors in the proposed network solutions. The breakdowns would be presented to the user to allow for the necessary business analysis to be carried out and to eventually allow this to be pursued to the level of presentation of a bill of materials for work to be carried out. The RIGs allocations follow the electricity distribution price control cost and revenue reporting *Regulatory Instructions and Guidance* (RIGs) framework.

Not all RIGs areas were able to be populated with values in the current SIM cost model version given the difficulties noted above with extracting consistent sets of costs from the business for non-standard (or even unavailable) items or as yet non established working practices and procedures. The divisions have been retained however within the cost model framework as this information may become available in the future (if such solutions are eventually looked at in greater depth or adopted).

4.11.1.2 Transformers

While there is an exceedingly diverse population of transformer models/manufacturers, ratings and ages on the network the SIM design was constrained to providing (and costing therefore) just a subset of what is currently available to be deployed in this area.

[3] DAR in the FALCON trials was extensively monitored and this required the implementation of the FALCON WiMAX monitoring network. The need for monitoring was however a facet of the trials since in the BaU production mode of usage, the limits and processes for successful DAR would have been established.

The standard sizes adopted by the SIM for proposed new installations were as follows:

Table 4 – Allowed Transformer Ratings

Type	Ratings, kVA
Ground Mounted Transformers (all three phase)	315, 500, 800, 1000
Pole mounted single phase transformers	15, 25
Pole mounted three phase transformers	15, 25, 50, 100, 200, 315

Replacing an existing transformer will be cheaper than installing a new one. Thus it was considered to be worth separating these activities into two separate types, so that the cost and man-hours implications could be calculated separately.

In looking at the costs, it was considered likely to cost more to upgrade from a 15kVA transformer to a 315kVA transformer compared to upgrading from a 200kVA transformer. However as it was unlikely that we would be able to find sufficiently robust cost data to make inclusion of this level of complication worthwhile the approach was taken to have a single upgrading cost regardless of the size of transformer replaced.

As a further assumption, as it cannot be known whether the infrastructure in place through a replacement operation is always sufficient to accommodate the change (e.g. can the pole take the weight or does a concrete plinth have sufficient weight bearing potential, or is a GRP enclosure large enough), this cannot be costed according to context. However a single level of assumed costs for modifying the infrastructure will be included within the unit cost of upgrade. E.g. the cost to upgrade to a 800kVA transformer will include an average value that covers plinth adjustments.

Transformers may or may not be re-used following their replacement and since this can't be known by the SIM (actually the NMT), a general assumption needed to be made and reflected in the cost values used. Were a transformer to be reused, this would effectively be a negative cost for the patch. The decision was made to assume all replaced units were lost to operations (i.e. not reused).

Single Phase transformers pose an additional issue. If a single phase 25 kVA transformer is overloaded then to increase the transformer size the upstream overhead line must be upgraded to three phase construction. Such complications need to be factored in to the way the algorithm for asset replacement is written.

Some ground mounted substations contain two transformers. Whether or not this could take place in practice would depend on the type of substation, with a typical "package" substation covered by a GRP housing would not afford the space for an additional transformer. IPSA was limited to adding no more than two transformers. This was seen as the best option to ensure site limits weren't ignored entirely but still allowed for load growth that could be assumed to be provided for by additional distribution substations, even though these were not explicitly modelled as additional substations.

4.11.1.3 Underground Cables

Three sizes of underground cable are used by the SIM. These are 95, 185 and 300 mm cross section. These are solid core aluminium single phase cables used together in a triplex pattern. When a cable is overloaded then the smaller size cable is not recovered and reused so there only needs to be an option to install a larger size cable along the original route. No costs are therefore included for underground cable recovery.

4.11.1.4 Overhead Lines

Similar design standards exist for 33kV and 11kV Overhead lines. A simplifying assumption has been made that while it is technically possible to upgrade the overhead line beyond the standard for 100mm2 cable Heavy Duty Construction to have larger conductors, this rarely happens in practice and it would be more likely to re-plan the network, perhaps replacing the overhead lines with underground cables or even splitting a feeder.

The options for the SIM are:

- 25mm2 HDC 17
- 38mm2 HDC 24
- 50mm2 AAAC “Hazel” 34
- 60mm2 AAAC “Pine” 45
- 70mm2 HDC 55
- *100mm2 AAAC “Oak” 66*
- 100mm2 HDC 77

There are two design standards using 100mm2 conductor size. Rather than support both options it was proposed to just use the Heavy Duty Construction variant.

Single phase 11kV Lines would only use the 25mm or 38mm construction standards.

4.11.1.5 DAR Costs

The DAR technique offers a method of using existing assets more cost effectively by making the most of their capabilities under different prevailing environmental conditions. In summary this means loading the assets more heavily when this will not have a negative effect on them which in turn usually means when the prevailing weather is colder (and/or windier in the case of overhead cables). During the FALCON trials, DAR sites are fitted with a number of environmental sensors which will aid in the analysis of the data taken from them. However this is only necessary during the data gathering and prototyping project activity. Once the operating parameters have been established during the trials phase, DAR can be implemented wherever it is suitable without instrumenting the electricity distribution infrastructure.

A small amount of CAPEX costs have been included within the technique to cover the installation of some monitoring / control equipment. It is likely that DAR will be more useful where there is an option to control loads to an asset where the weather and previous loadings result in a lower than usual ampacity. This CAPEX also covers the work necessary to investigate candidate DAR locations/network elements to determine whether they are suitable for participation in this technique. For example, it may not be considered suitable for more aged assets to be pushed in the manner required under DAR conditions so some checking may be required.

The operational costs for DAR are confined to the per usage component associated primarily with loss of life of the asset arising from it being used in an extended operating envelope. There is no ongoing maintenance charge specifically attributable to the asset being involved in DAR, and normal BAU maintenance will manage such assets.

Thus for DAR, the only costs derive from the loss of life element associated with technique deployment and the investigative work required to establish that the technique can be deployed in a given place.

4.11.1.6 ALT / Meshed Networks Cost Elements

To support ALT (the case is also true in a Mesh implementation) it is necessary in most cases to install a remotely controlled switch/circuit breaker to enable the load transfer required from the deployment of the technique. This clearly means that there is a CAPEX cost associated with setting up an ALT location if this has not already been done (which the technique accommodates).

4.11.1.7 Energy Storage Cost Elements

To support the use of the battery technique it is necessary to install actual energy storage equipment. This clearly means that there is a clear CAPEX cost associated with setting up an ES location. There is also a very clear OPEX cost required for the maintenance of the whole battery equipment set as well as a definite per usage (loss of life) cost. This makes this technique slightly different from the others in being so clear cut, though at the same time as this is wholly new technology in the UK, there is very little experience within WPD of the use of energy storage and naturally therefore correspondingly little cost information, particularly on the maintenance element. The FALCON project itself is thus likely to be the best source of battery cost information.

Battery Installation Costs
This CAPEX element comprises materials, expenses and labour elements. It may also include legal costs as it is likely that additional ground footprint is required for the siting of the units.

Battery Ongoing Site Management Costs
This OPEX element comprises materials, expenses and labour elements. Batteries deteriorate when not used regularly in addition to and analogous to per usage costs.

Battery Per Usage Costs
These are primarily derived from loss of life / capacity fade resulting from usage and losses.

4.11.1.8 DSM/DG Cost Elements

These two commercial techniques will be treated together as their management is identical. Note for DSM that Demand Side Response (DSR) is the more proper term to use.

These techniques must also be viewed for what they are and the SIM will need to operate them basically in accordance with how they would be deployed in the real world. It is worth describing this here for completeness.

The ideal time to deploy DSM (and/or DG) is to offset a capital cost (CAPEX expenditure item) through a period of uncertainty, allowing a situation to develop to a point where it is understood how the engineering response should actually be constructed including perhaps the issue having been deferred indefinitely. This might therefore allow, say, a DSM strategy to be deployed to the real world network during an interval while a new development (that might add load to the network) is decided upon. If the full development should not proceed, then DSM can bridge the gap while the full extent of the engineering response required becomes clear. The SIM might therefore model similar scenarios, providing a more realistic overall view.

It can be seen therefore that DSM/DG are operated more as a form of insurance (and/or fallback capability) rather than being a full, complete, final solution to a network capacity issue and the SIM result set should reflect this reality.

Business Operating Model

There is some significant uncertainty at the present time as to how the management of these techniques would be carried out by WPD going forwards. There are different operating model options available to the business and these options will impact significantly on actual cost values (with the trade-off being made against control of the process). The main options, which are still being assessed, are:

- To call on the services of Aggregators external to the organisation to manage this function. Aggregators work by taking a share of revenue paid to the participating customers by the DNO, so there is no additional cost to the DNO , though it is likely that the prices paid to the customers will reflect the cost of administration.
- To operate a dedicated team within WPD responsible for the management of DSR and DG. The overall function would include the separate aspects of:
  - recruitment of participating organisations and management of the contractual aspects of arrangements and,
  - Dispatch/cease operations management.

If this approach were to be adopted, the teams might be Run as profit centres and be self-sustaining, covering the various operations required.

Certainly the issues are extensive as there is also the background question of the nature of WPD’s active participation in service provision, moving this more into the realms of a DSO. This whole area has evolved significantly over the last 18 months and while a view on this is being derived so as to move this forwards at the present time, no decision is expected in the immediate future as to whether an in-house team or aggregator model would be used, and how WPD should approach the broader questions that are raised.

A further complication also arises in deciding how to assign the cost elements to the SIM preferred cost categorisations (CAPEX/OPEX). DSR/DG has no associated assets, and all costs can therefore be effectively assigned as operational costs. However an argument can be made that the set up costs for establishing service provisions that will last for many years could be capitalised. Again this depends on the operating model chosen. So, should an in-house team be the chosen approach, the initial set-up costs could be assigned to CAPEX with an operational component, or the whole of the overall management process could be set up as a single up-front CAPEX cost.

The model chosen is effectively an accounting preference.

In terms of actual costs, £300/MWh is the currently established Per Usage figure and this was assumed for the SIM cost model. This is from information provided from within the FALCON team, and is itself based on a number of operating assumptions which may need further validation and which may therefore result in further revision to the quoted figure.

CAPEX and OPEX costs cannot be established presently because of the uncertainty described above. Until this is decided upon, the range of possible cost values is potentially large. However it is possible to make the simplifying assumption for now that the Aggregator model will be used, and that in-house costs are therefore zero on CAPEX and maintenance OPEX, adopting the figure quoted above for the per usage cost (on a per MWh basis).

4.11.1.9 Disturbance Costs

Following the example of the Transform Model the SIM holds and uses a value for the cost of disturbance for deploying a number of the interventions. The costs are associated with installation work and are designed to cover disturbance/disruption to the public for works such as digging the roads up to bury underground cables etc. Benefits have not been included explicitly at the current time as these are much more difficult to quantify though they do offset the disruption factors in a number of cases, for example converting an overhead to an underground line in an area of outstanding natural beauty is clearly desirable but is not necessarily readily modelled as a cost benefit. This may be a subject area for further exploration using the SIM.

4.11.1.10 Annual Network Cost Metrics

As described more fully in Section 2.9.1, the SIM tracks a number of metrics at the network state rather than intervention (patch) level. Some of these metrics, but not all, map onto a cost. These are:

- CML (Customer Minutes Lost). ED1 values are set by the regulator and used for the cost model. The cost is a multiplicative effect of base cost per customer minute and number of minutes off for the total number of affected customers

- CI (Customer Interruptions) which are computed as a flat value per user interruption.
- Losses are comprised of both real I^2R and accounting losses. There is no losses incentive value for ED1 and it has been suggested that DR5 values are used and scaled back to a proposed 80%.

In addition where issues with Fault Level are reported, these are costed very high so that these are not expanded further within the SIM search space. This is because there are no techniques to apply to resolve Fault Level and such issues would be beyond the scope of the prototype SIM.

4.12 SIM Support Tools

This section describes the tools initially envisaged as part of original SIM design, but rather, were developed during the project in response to specific needs. In addition to the SIM Inspector and report generation tools described previously, another external result view tool was also deployed to allow the viewing, (within the network editor) for test and validation purposes, of network states whatever their outcome. The SIM originally implemented viewing facilities for actual success condition *Result States* where the network was fixed. However it was realised during the integration work that in order to be able to validate the SIM results, a facility was needed that could look at any state fixed or not – i.e. not necessarily limited to those states featuring an end result network solution. Additional tools were developed that allowed extracting of complete network states from the SIM database for QA and validation purposes, creating executable replay scenarios that mimic parts of SIM search process also for QA and validation purposes, technique patch inspection, load profile conversion and parsing of compressed binary log files.

4.13 Data Issues

A number of data issues and assumptions relating to data were flushed out by the integration and especially by the validation testing of the SIM.

4.13.1 Network Area

While the FALCON trials area core network consisted of 6 primary and some 800 secondary substations, it was determined very early on in the design process for the supporting database that information relating to adjacent feeders would also be required by the SIM. This is because in particular the mesh and load switching techniques need to evaluate options outside the core area. This expands the number of secondary substations by a further 1200 locations. This provides a clear recommendation regarding network extent to any organisations which may need to conduct a similar form of analysis.

4.13.2 Defaulted Loads

It was found that not all substations in the main core and periphery (original or across NOP) Authorised Network Model areas had an associated load. On investigation it was found that some 20 substations had no MPAN and therefore no actual load. A couple of missing substations were present with MPANs but a decision was taken not to estimate their load at greater depth as one was on further inspection found to be a building site and the others fed only a very small number of customers so would not introduce too much inaccuracy.

The default opening behaviour in the NMT for such cases was to set the load to a default value equal to the rating of the transformer. Taking into account losses, this was found to trigger constrained asset failures in the running SIM and a modified approach had to be taken. Since no load data was available it was decided that these loads would be set to zero for the duration of the analysis.

4.13.3 Modified Loads

It was found that a straight acceptance of Energy model output datasets imported into the SIM was not an advisable approach to take as this resulted in the use of a number of profiles that were either under or overestimated by the model and which therefore (in the case of overestimated values) caused an excessive number of network constraints to be generated by the Running SIM. In consequence a data adjustment capability was added within the load profile importation process. This adjustment capability provides the SIM with an opportunity and a mechanism to effectively adjust the driving data in use and was considered a useful feature to deploy.

An analysis of the reasons why the Energy Model output deviates from actual measured loads is not within scope of this document, but does fall in scope of the FALCON Load Estimation Final Report, where more information may be obtained if required. It is sufficient here to note that there are many reasons for the sort of deviations noted from the Energy Model (which is still being refined) and to provide the example of the sports arena where the local substation load clearly depends on the season and the fixtures list, the latter being a difficult component to account for within a modelling system.

A SIM adjustment was also put in place for year 1 handling by implementing an extra option to allow the use of the traditional reinforcement technique only on that initial interval. Another option (not used) would be to define and they employ a network patch in the first year.

A variant of the facility also allowed for the adjustment of the load profile sets to reflect situations where these need to be modified for other reasons. The first use of this was to model generalised demand side management i.e. that which could be expected to result from time of use tariffs rather than from individual contracts placed with DNOs. This allowed for a configurable degree of load smoothing for sensitivity analysis.

4.14 Handling Larger Network Simulations

As a pilot project there were a number of uncertainties around SIM outcomes and one of the major concerns from the early design phase related to the performance of the SIM when conducting larger evaluations. The SIM is a very flexible tool and has a number of dimensions over which it can operate including:

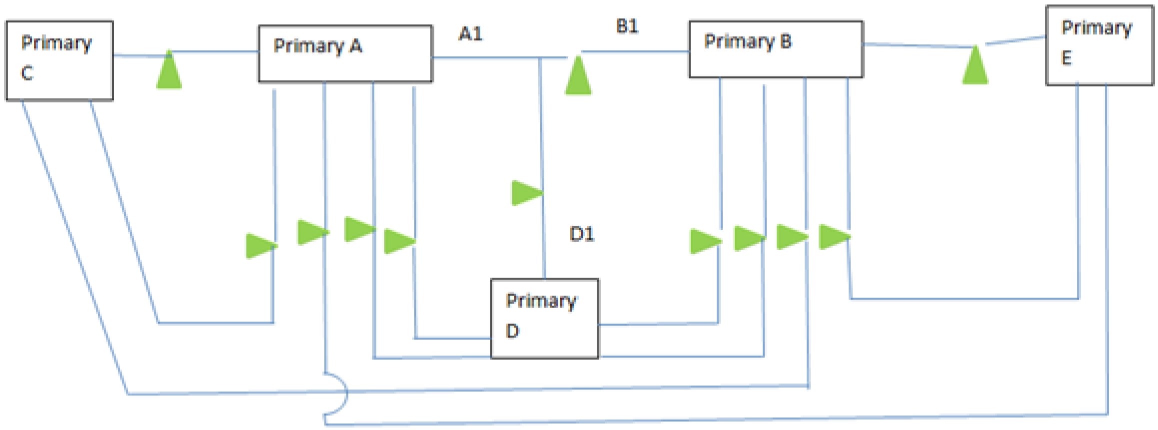
- The simulation timeframe – the number of years modelled into the future. This has to correspond to the objectives of the Run;
- The number of techniques deployed to rectify network constraints, and optionally, the order in which they are applied Again this has to correspond to the objectives of the Run, although simpler experiments to probe the network response using current strategies (i.e. traditional reinforcement only) mean a much reduced workload for the SIM;
- The network extent (See below);
- The type of search being performed (A* or depth first)
- The number of characteristic days being modelled.
- Of particular concern from the outset was the size of the modelled area, and the prototype SIM was designed to operate on a single primary area, though be capable of providing an analysis of the core network area covering the six main FALCON primary substations. During the development, integration and test phase and until a number of optimisations and performance improvements were put in place, it was found that execution times were very long for the experiments which stretched the SIM in all of these dimensions, in particular it was expected that the IPSA wrapper code processing time would scale approximately linearly as a function of the number of busbars in the selection.
- Difficulties were also encountered with memory utilisation on the SIM host platforms. As an expedient, it was therefore determined that the SIM should be adjusted so that it would be possible to assemble several Runs, each covering a smaller network extent, into single analysis of a larger network extent. Thus required a number of difficulties to be overcome but provided the SIM with enhanced capabilities as well as providing the results required for this Report.

4.14.1 Resolution of Network Area Overlaps

For full flexibility in the analysis, the Project determined that it needed to be able to combine multiple SIM Runs (predicated on the same starting conditions) to present an analysis for larger network areas assembled from a number of smaller ones. This approach also mitigated against the possibility that the SIM Runs took a long time (or required too many computing resources) to produce results for the longer simulations such as those envisaged for this report.

In order to split a large SIM Run (covering for example a six primary area) into multiple sub-Runs consisting of 4, 3, 2 or 1 primaries it becomes necessary to handle overlaps between the area and avoid double counting results from adjacent feeders. These effects arise because as well as the selected primaries, feeders that are on the other side of normal open points will be included to support N-1 analysis. The same applies to the modelling of the Automatic Load Transfer and Mesh network techniques. To illustrate this, in the diagram below Feeder A1, connects Primary A with Primary B via feeder B1. It also connects Primary A with Primary D via feeder D1.

Figure 17: SIM Network Area Handling - Managing Overlaps



Source: FALCON Project

There is no mechanism in IPSA or SIM harness to discriminate between the primary feeders selected by the user and those that are added by tracing beyond normal open points and therefore the resolution of network issues will apply to all the network regardless of whether it is part of the selected primary or an adjacent feeder.

Therefore, if there is a network issue on feeder A1, this could be resolved by applying a patch to A1 for all Runs in a group of Runs which together build a single set of results for a larger network area, referring to the table below this would be Runs 1, 2 and 3. By adding the results of Runs 1, 2 and 3 the analysis will overestimate the investment on feeder A1.

Run	Primary selected	Feeder selected as part of primary selection	Feeders selected to support N-1 analysis
1	A	A1	B1, D1
2	B	B1	A1
3	D	D1	A1

Similarly if a patch is applied that affects the normal open point between A1 and B1 or A1 and D1 then this will also be replicated for Runs 1, 2 and 3.

To resolve the over-reporting of patches, and hence the number of instances a technique was applied or the costs, an alteration was made such that IPSA could associate both network issues and patches with feeders. A feeder needs to be uniquely identified by the combination of Primary ID and Feeder within it.
In most cases allocation is straightforward but feeder membership is complicated by algorithms such as ALT and Meshing. It was determined that all assets be initially associated with a feeder and subsequently maintain that relationship regardless of ALT / Mesh changes. Where a patch is applied at a normal open point the patch will relate to the feeder that the NOP switch is associated with.

Reports can then exclude issues and patches applied on adjacent feeders allowing the results for each primary to be combined without overlap.

4.14.1.1 Network Performance Calculations

CIs and CMLs are calculated for the full network, i.e. for the selected primaries plus adjacent feeders. It is difficult to split this computation up, if the adjacent feeder is excluded then the alternative source and the network used to backfeed the primary cannot be modelled correctly. This would result in higher CIs and CMLs and unrealistic power flow analysis values. The best way to resolve this is to perform the analysis for the full area under consideration. While feeder level CML/CI calculation would be preferred, this is acceptable as what is of interest is the change in CML/CI from one year to another.

4.14.1.2 Network Losses Calculations

The losses calculation in IPSA was altered to ignore losses beyond the normal open points.

4.14.1.3 Other Network State Metrics

If adjacent feeders were to be included in the calculation of other network state metrics, e.g. average network utilisation, then values for separate neighbouring networks cannot be merged easily. Adjacent feeders have been excluded from network state metrics.

4.15 SIM Validation

Validation of the SIM outputs was understood to pose a serious challenge from the very start of the project. With many tens of thousands of network states being explored during a single experiment Run, the sheer numbers involved and scale of the undertaking meant that a considered, pragmatic way of carrying out result validation was necessary.

Validation is the means, as part of the overall testing approach, of actually establishing the accuracy of the outputs generated by a system under test. It is an integral part of the test phase. Validation of results also features in all test stages when the developer effectively asks himself whether a particular testing outcome is expected and can be confirmed as numerically correct where applicable. For the SIM a specific set of validation exercises was necessary however at the higher levels of integration and system testing.

In the first instance the use of IPSA, an established load flow analysis tool of known pedigree and accuracy, provided a first level of results assurance by virtue of the large user base which has qualified it as an engineering tool over many years.

Beyond that, in the validation phase, once a SIM experiment Run had been conducted, a sense check needed to be carried out on the result. The Sim Inspector tool that produced the tree view of the Experiment was very useful for this activity. However the manual process to follow the states through was very laborious and could only ever touch on (and validate) a very few of the possible implementation pathways. Further – the “depth first” search space exploration needed to be used in this phase as the A* heuristic driven SEARCH was not as deterministic in its outcomes.

Thus the SIM validation was based on a sampling approach inspecting a selection of network states almost at random in a sequence of overloads/intervention operations and following the actions taken using the SIM support toolset. The approach also checked:

- That each technique application was sensible and understandable and resulted in new network states that could be understood;
- How combinations of applied techniques operated;
- That the overall progression of solutions to the production of a Result in the final year could be explained and made sense.

As the integration process was more complex than had been anticipated the validation phase of the project also included a degree of debugging. One of the recurring issues was despite the large volumes of data that are exchanged between the NMT and SIM harness, it was difficult to determine the cause of unexpected behaviour. For example, IPSA will not always generate patches for all potential techniques to resolve an issue. This may be due to lack of any locations where the technique could be applied, or that the patches that are created do not improve the network, or because an error is preventing IPSA from assessing the technique suitability or from generating patches. A “patch checker” application was developed to help determine whether patches should have been returned. Similarly tools to provide enhanced logging were created and adapted. As well as assisting the validation process, these rapidly created applications suggested that a great deal of enhancement could have been achieved in the RAD cycles.

4.16 Development Feedback from Running the SIM

A large amount of indispensable feedback was derived from operating the SIM. This feedback was useful to the developers and to Network Engineers and for the latter, the result analysis is covered in Section 6.2.1 of this document. In this section, consideration is given to how the RUNs of SIM trials, tests and production informed the development of the SIM as a modelling tool to improve performance and other system features.

4.16.1 Host Environment

It became quite rapidly evident that with the very large amounts of data used and generated by the SIM that the distributed client/server architecture of the system would make too much demand in terms of network load to be usable. In consequence, the architecture was collapsed onto single host machines. Because the server side is LINUX based, while the client side is Windows, this required the deployment of a virtual environment to the hosts to allow for this diversity of operating systems in use.

Tuning was also carried out on the hosts to set parameters such as VM page/swap file sizes.

4.16.2 Parallelism in Production Runs

Given the long run times seen for the larger network simulations during the final stages of integration and especially once all intervention techniques were being deployed in the experiments it was deemed necessary to deploy a bank of modest cost but powerful SIM host platforms for the actual production Runs. In the final production mode, 7 PCs were deployed as SIM hosts although one of these was also being used for development and testing. With six dedicated machines, this allowed for significant parallelism while the responsiveness of the SIM was being determined. The ability to do this rapidly showed that the basic design of the SIM was flexible enough to accommodate such a temporary change in direction.

It was necessary in this approach however to ensure that data from multiple Runs of the SIM requiring to be merged (refer to Section 4.14.1) to yield a larger coverage/analysis area was available on a single host to avoid the need to merge databases across different machines. The parallelism was therefore implemented so as to conduct a SIM Experiment per host (for example, a set of Runs evaluating the network against a given demand scenario) with sub-elements of the overall Experiment (by primary) carried out in turn on that host.

4.16.3 Additional Functionality – Busbar Replacement

During the testing phase it became apparent that from time to time switchgear busbars would be reported as being overloaded. This had not been anticipated and there was no technique implemented to represent a switchgear change. Therefore the technique to replace a section of cable with one of a higher capacity was modified to be applied to busbars. This is useful learning and suggests that a switchgear change technique would be a useful addition to the tools. This would also potentially expand the possible uses of the SIM as being able to model the replacement of transformers, switchgear and linear assets provides a good foundation for modelling condition related asset replacement.

4.16.4 Execution Optimisation

A number of these were put in place as described in this section.

4.16.4.1 Order of Function Application

It was found that resolving issues by selecting the worst issue first had a beneficial effect on processing. This is because ordering of the issues by severity and then attempting to fix the most severe issues first often fixes other issues as well.

It was also found that applying techniques in a preferred order and, for example, favouring DAR and Mesh over batteries or creating a new split feeder, was seen to result in fewer redundant patches being created.

4.16.4.2 Nature of Host

The SIM was initially designed to run on a cluster with multiple *worker* machines simultaneously evaluating network states.

1. The SIMH internal APIs are stateless, so no *machine* of any type assumes a particular sequence of API calls are to be sent to it;
2. The same applies to the NMT APIs;
3. The RabbitMQ/AMQP messaging server has been used and this is particularly suited for distributed systems – it actually distributes API calls between machines of the same type automatically;
4. A system is in place for automatic management of worker machines that permits the scaling of the machine pool up or down depending on the real-time load.

However, a shortcut in the server code has been instated so as to permit the bypassing of the messaging server based architecture detailed above in the case of single-machine deployments – such as that adopted for the latter stages of the FALCON Project.

Each instance of SIM harness programs consists of number of modules. Each module declares a number of API call handlers it provides to the *libmsg* module. Thus the libmsg module knows what API calls can be executed immediately on the same machine and what calls must be forwarded to the messaging server to be consumed by third parties. This is where the "bypass" happens – if the SIMH detects that a function is available locally, it calls it immediately.

4.16.4.3 Passing of Large Data Items as Files

There are a number of data types that are known to be large and immutable within context of a particular experiment run. Examples include demand scenarios and ipsa I2F network representation files.

Files of the former type, The Demand Scenarios - these files were far too large to be effectively accessed via the database. As a result, demand scenario data is held in zip files (one zip file = one demand scenario) and these zip archives are distributed manually via the usual means of file exchange. The SIM database only stores the corresponding hashes (md5 & sha1). Upon startup, the SIM Harness (SIMH) locates those archives on the hard drive of the machine and compares their hash sums to values stored in the database. If values do not match then the startup procedure is aborted.

For each NMT-related call, demand scenarios are converted into "IPSA format". This involves unpacking records for a particular year and set of network loads from the source archives, merging these into a single data structure and marshalling of the data into a file on the hard drive. As each of the "year + load profiles" combinations is static, the SIM re-uses those files when it is asked to do evaluation for the same experiment / year / load profile combination. It also keeps backups and automatically restores these if necessary.

For the latter I2F Network files, the database stores md5 and sha1 hash sums for any file added into it (including therefore the I2F files) which can be used to uniquely identify a particular file. To avoid transmitting the content of these files for every relevant call the SIM Harness saves the I2F files into a temporary directory and re-uses the file after verifying the hash sums (hashes are sent to the caller each time a file record is requested from the ORM). This saves considerably on repassing of data already held.

It is expected that future SIM enhancements could feature more facilities for distribution and verification of large binary files.

4.16.4.4 Reducing the Number of Invalid Patches Generated by the NMT

Patches which created more failures than they fixed were flagged to not be expanded further Additionally, after evaluating a network state with a new patch the SIMH computes the difference between failures returned for the given network state without that patch and failures returned for a network state with it.

A patch is marked invalid if:

1. A number of failed asset groups increases;
2. Failure set does not change (patch does not affect the network);
3. No failures have disappeared and none of the failures have reduced “magnitude” value.

4.16.4.5 Processing Optimisation – Component Structure and Placement

It was necessary to move the A* search algorithm to the ORM machine due to performance reasons and in a future change it is recommended that the “MCP” (control) and “ORM” (db) machines are merged as their functions are tightly coupled.

4.16.4.6 Reducing the Number of Search Branches

It was found that by always fixing asset groups in order some performance improvements were rendered possible. Thus the SIM only attempts to fix an asset with most of the failures for each network state. This assumes that when this failing asset is fixed, any failures remaining will be fixed in the child states of that given parent network state.

4.16.4.7 Speeding up Error Recovery by Implementing Advanced Error Handling

Timing out NMT calls where the evaluation time (measured by the system) exceeded a specified threshold limit was found to be beneficial for ensuring that the RUNs proceeded to completion. Such states were flagged as bad states and not expanded. It was believed that the complexity of the analysis or some recursive operation would be in play in such cases and this aspect would bear further investigation. Meanwhile the pragmatic approach to solving extended processing times was taken and the NMT module was moved into separate sub-process that would communicate with the SIM Harness control elements via UNIX pipes (FIFOs). This sub-process can then be terminated and restarted when any of the following is true before the moment when the SIMH control element passes a new call data to it:

1. It allocates more than 3gb of RAM or more than 8gb of VRAM (RAM + swap file);
2. It fails to respond to “ping” sent over the comms pipes;
3. It is killed and restarted every 200 invocations anyway;

A restart is initiated when:

1. Sending data to it takes more than 60 seconds;

2. It fails to ACK call data sent to it within 15 seconds;
3. It produces no logging output nor returns a result within last 5 minutes (up to 10 * 5 minutes in total, then it is terminated).

4.16.4.8 Reducing number of branches by A* learning speed coefficients (prediction pressure)

Refinements to the A* search method were made so as to incorporate a learning process that allowed the SIM to build up a picture of expected costs for each year. This can then be used to direct whether the search algorithm should expand the options in a particular year further before expanding the search in later years. Refer to Section 4.8.3.

4.16.4.9 Caching of Patch Results

This intended optimisation did not work because asset groups are not independent in the final analysis. Failures fixed by a patch are actually affected by failures present on the network.

4.17 SIM Nodal Modelling - Key Conclusions

During the validation period, and later when performing the preparation for, and then the actual, SIM Runs, a number of points emerged some of which (relating specifically to the software) are covered in the previous section of this document.

One of the main observations was that the number of failures in the initial starting year and the time taken to process it were quite large. To address this it proved necessary to apply some adjustments to the energy model output for this initial year where the model appeared to have overstated the load in many cases. The adjustments were supplied as supplementary values and these were used to subtract from the load levels loaded direct from the energy model. Refer to Section 4.13.2 for more details.

The actual number of days within the year mapped onto each of the 18 characteristic day types was refined during the testing when it was found that these had not been set to the necessary values and were causing too many overloads. The final values against each of the 18 day types were set as follows:

- Autumn Saturday: 8
- Autumn Sunday: 8
- Autumn Weekday: 39
- High Summer Saturday: 6
- High Summer Sunday: 7
- High Summer Weekday: 30
- PV Peak: 1
- Spring Saturday: 7
- Spring Sunday: 6
- Spring Weekday: 34

- Summer Peak: 1
- Summer Saturday: 10
- Summer Sunday: 10
- Summer Weekday: 50
- Winter Peak: 1
- Winter Saturday: 22
- Winter Sunday: 21
- Winter Weekday: 104

This annual breakdown, based on these characteristic day types, could form an area for future investigation given that the early results from the SIM are showing that the omission of some day types would not be likely to underestimate network issues. To further optimise SIM execution times it would potentially be possible to combine "all other days" to a single day type allocation with the number of days within that new collection being set to the sum of days of each type forming it and with a single load profile representing this combined "all other day" type. So, for example, it is very unlikely that the Spring Sundays will ever be constraint generating days. By such means, if the number of characteristic days can be reduced to around 8 in total, this could allow the SIM to Run at a rate of some two to three times faster than at present. While the accuracy of the network state metrics would be reduced this seems an acceptable trade-off.

4.17.1 Specific Conclusions

1. The future SIM requires an energy model that is scalable across a whole DNO region. This could be achieved by considering alternative sources for data to populate demographic attributes. A possible way to achieve this will be to use smart metering data to identify customer archetypes from which occupancy and demographic data can be derived.
2. While the SIM has not yet hit a limit in terms of the time required to Run experiments, the SIM project workstream has already started to think about new techniques to reduce the number of evaluations by several orders of magnitude. These include restricting the day types, limiting the variations in each technique application, adjusting the thresholds for issues.
3. Data sources are not always present (or in the correct format) within the organisation (WPD) which are consistent with the type of information needed by the SIM, in particular for specifying the network and cost model and qualifying (calibrating) the load curves generated by the energy model;
4. The core network "area of interest" to be used as the focus for SIM investigations expands considerably when the necessary adjacent feeders in the peripheral area to this core are added in so as to permit a complete analysis within the core. The ratio of the size of the periphery to the core (measured in terms of the number of substations) within the FALCON SIM Authorised Network Model (having a core area involving 6 primary substations) was around 2:1;

5. Consideration of how to divide up a core network area for analysis into smaller chunks (based on groups of primaries) needs to take into account linked feeders which may span the subdivisions. Primaries were analysed individually due to run time constraints but if these barriers can be overcome then analysing small groups of primaries together would be preferred.
6. A more fully integrated cost model data management GUI is required. The prototype SIM used MS EXCEL as an external source of details and a values repository from which CSV files of generated values could be exported to the SIM. This resulted in a more fragmented user experience;
7. Obtaining the source data for the cost model required considerable effort not least because of the new technologies and procedures used on FALCON which were naturally not included the current BaU cost framework (ES, DSR etc);
8. Trials feedback was often difficult to incorporate due to the different nature of information used for real time operation and planning, or a specific instance to generalised application;
9. Data analysis (especially during integration and validation testing) required the development of inspection tools external to the SIM in order to facilitate checking (validating) of the results generated by the SIM. Some of the functions of these inspection tools might be usefully incorporated into a future SIM version, but for the moment remain as peripheral support facilities;
10. The type of constraints are characteristically different across different areas of the network. Thermal constraints are likely to occur anywhere whereas voltage constraints are more common on overhead circuits. This should be remembered when picking a sample primary for testing or evaluation;
11. The volume of data needed to support the SIM operation is very large indeed and an approach to its management for real-time access was needed to be derived to prevent out of memory conditions on the host platform.

4.17.2 Future Enhancements and Development Strategy

Looking at the SIM prototype design it is possible to identify a set of design limitations, and it is then possible to consider a set of future enhancements and adjustments to the SIM that would remove these, or at least to state the general areas to where these enhancements may be directed. We consider that the enhancements that were identified by the SIM workstream of Project FALCON fall naturally under the following main thematic headers:

- Modelling granularity;
- Development rigour;
- User management;
- Implementation complexity;
- SIM overall context and supporting toolset;
- SIM functionality and plug-ins;

- Performance and optimisation;
- Data handling capability.

It should be noted that the SIM prototype was developed with the possibility in mind that it may become a BAU or even a commercial product.

4.17.2.1 Further Techniques

The SIM currently implements seven techniques and these have been evaluated by the FALCON project (or in the case of traditional reinforcement, this is known from standard BAU processes).

Enhancing the SIM to include a switchgear replacement technique would allow for issues to be managed more comprehensively and would provide a foundation for expansion of the SIM to include condition related replacement.

In terms of other new techniques, it is recommended that there should be a future review of other LCNF projects (eg. FLEXDGRID and Fault level mitigations) and other research conducted to see which techniques look promising. This effectively means assessing techniques for which the real world trials have already been carried out by some other third party.

The next stage would be to see whether the technique could be modelled in IPSA by writing new code in the same way as the FALCON techniques have been coded. FALCON informs these decisions and approaches in terms of such considerations as balance of thermal to voltage issues and therefore whether it made more sense to pursue techniques that resolve thermal or voltage issues.

4.17.2.2 Future Adjustments Required in the NMT

NMT Network Data Manager (NDM) Limits

The Network Data Manager is the SIM module which manages the specific SIM data and is scaled to suit a prototype SIM only. For networks with large numbers (many thousands of busbars), the NDM would require considerable expansion in order to effectively manage this size of data set. The SIM overall itself would also require additional adjustment to handle larger networks based on both limitations in performance and resource usage terms.

Load Whole Network

The NMT used for the SIM is based on the existing IPSA Power System Software and its associated network files. IPSA currently provides a graphical interface for viewing, editing and analysing distribution networks up to 25000 busbars. The NDM should ultimately be able to handle significantly larger networks representing the 11kV distribution systems of Network Operators. These networks typically comprise hundreds of thousands of busbars (including junctions, nodes and joints). While the current IPSA software version is not optimised to handle networks of this very large size developments could be undertaken in the future so as to permit this. The existing Milton Keynes network as imported into IPSA has around 7000 busbars and is therefore within the limits of the current NMT which is set to handle over 20000.

Performance Issues

Performance enhancements would be required in IPSA to open, view and modify networks comprising hundreds of thousands of components.

Initial testing of the NMT with networks comprising 100,000 busbars indicate that the time taken to open data tables and networks is in the order of minutes as opposed to seconds. Navigation of geographic diagrams is also slow.

The scope of enhancements needed to manage this capability increase would include improvements to the diagrams, data tables and dialogs to ensure that all these user interface components operated to acceptable timescales. This would require performance improvements to dialogs and other user interface features to reduce the requirement to refresh the diagram following component editing or analysis. For example the time taken to open data tables or to pan and zoom on the diagram would be reduced.

Selection dialogs would be enhanced to provide component filtering by metrics such as Primary and feeder name as well as just voltage level. This would also be extended to the data tables and results tables to ensure that they remain responsive for large networks.

The approach favoured, and currently being developed by IPSA, is to move to a Network Data Manager approach where the network data is stored in a database. This new application is being optimised for handling and analysing very large networks as commonly encountered in DNOs.

Network Imports

The Authorised Master Network (Authorised Network Model) represents the power system components that make up the current distribution network. It is created from the WPD corporate databases and converted to the NMT specific i2f format before analysis can be undertaken.

A two stage process is currently required to convert the WPD network data from corporate databases and systems such as PowerOn Fusion to the IPSA NMT file format. This requires importing data to an intermediate staging database followed by a Python scripted conversion to the IPSA i2f format.

Some parts of this process would require to be automated in order to better handle the larger data sets associated with the full DNO distribution network. This may include combining both stages into a single process and providing a mechanism to process only the data changes made since the last conversion.

A different network storage mechanism may be implemented for the NDM and NMT based on storing the network data in a database format instead of the text based i2f format. This would reduce the complexity of the conversion steps and the potential errors that they introduce. This would allow the NDM and the NMT to read network data and directly from the staging database or similar.

One common data format used for these types of data transfers is the IEEE CIM format (Common Information Model). Many SCADA systems and software packages have the ability to import and export CIM data formats. PowerOn Fusion has this capability and it is also being added to IPSA.

Network Area Selection

The NDM provides the mechanism for selecting a section of the network model to be used for the SIM analysis. This is necessary as a full DNO network model is expected to take a considerable time to analysis and distribution system design activities usually consider a single Primary or feeder at a time.

The NMT performs analysis on the full extents of the network that it receives from the SIM. The NMT currently has options to select individual feeders and adjacent feeders which are expected to be sufficient for the initial phases of the SIM rollout.

The future extended NDM should provide a more flexible selection of a section of the full network model which can then be passed to the SIM for further analysis. The selection of the network to be analysed can be undertaken as described below:

- The NDM will present a list of all Primary substations from which the user can select one or more Primaries (it does this in the prototype SIM but the list is small);
- All components and feeders downstream of the Primaries will be selected;
- The selection should include the 33kV side of the Primary transformers;
- The selection will include all associated patches for that area. This patch selection can be edited later;
- The selected area will be identified and highlighted on the diagram.

Following selection of a network area and associated patches a button would be enabled to allow the user to return to the SIM application. This process would also pass the network selection data back to the SIM to enable analysis to be undertaken. The validation of the selected patches within the selected network area would also be undertaken at this stage. The validated network and patches would then be saved as an IPSA i2f network file which may be used by the NMT for analysis.

Technique Data Inputs

The techniques as implemented in the SIM take a number of inputs that feed the algorithms specified by Aston University. These data points are discussed briefly below.

- For soil data the DAR technique requires soil data for defining the environment of underground (buried) cables. The thermal conductivity of the soil in the immediate vicinity of the cables is very important in this respect. Originally it was considered that FALCON could provide detailed inputs to the corresponding SIM DAR model for underground cables by obtaining a set of soil type polygons, matching these geospatially to the cable routes, and then breaking each cable span down into sub-spans, each of the latter holding its matching soil type as an attribute, and thus deriving the thermal capacity of the soil for each discrete cable section.

Further investigation, however, revealed that this would not be a practicable approach for FALCON and it was decided that no soil data would be included in the Authorised Network Model. The current SIM DAR cable thermal modelling models therefore assume a fixed value for parameters like thermal diffusivity. The thermal conductivity/resistivity of soil is not just a function of its type, but also of its moisture content. Not only is the latter itself a sensitive parameter in estimating the soil's thermal properties, but it is itself a function of several other parameters including the amount of recent rainfall and the typical height of the water table in the vicinities of the cables. Even producing localised moisture estimates for the five or so seasonal types of scenario days for the SIM models would be a non-trivial modelling exercise requiring several additional datasets. Though WPD has in fact purchased a soil dataset from the British Geological Survey (and is also utilising some data from Cranfield University's LandIS soil database), this was obtained for the purpose of identifying how deeply earthing spikes need to be inserted at various locations, so incorporates electrical resistivity data but nothing about its thermal behaviour. Obtaining additional data to fill this gap would have incurred additional scope (and costs, which had not been provided for in the FALCON budget and could form a subject for future work).

- For cable ducting data underground cable conduits are not well catalogued by the WPD systems. The master EMU dataset holds a 'fully ducted' flag against each underground cable section. These are obtained from the table data extracts and populated against the corresponding branch spans in the Authorised Network Model. Unfortunately no additional information, such as any details of the duct itself or where more than one cable share the same duct, is available. This is mainly a data limitation with impacts on the accuracy of the techniques. Any drive to improve this data would very likely improve accuracy, however the effort is not in the SIM itself but in the feeder data systems/databases and given the hidden nature of underground cables and the considerable difficulties in direct inspection for a data gathering exercise is unlikely to change. It may be sufficient at an approximation to assume that if any cable length is in a conduit it represents the "weak point" of the cable, so cable conduit ON/OFF may be all that is required.

SECTION 5

Authorised Network Model Production

The Authorised Network Model (Authorised Network Model) is the representative view of the network on which the SIM will operate. It is constructed from operational sources of this detail at a nodal and connection level using the elemental constructs needed by the NMT. These data elements provide the SIM with the accurate information necessary to conduct its power flow and other analysis. It also allows the SIM to make meaningful representation of the network under consideration to the SIM user.

The network model available to the SIM is only as good as (and is therefore limited by) the network information held in the BAU data systems of the DNO which are extracted and repackaged for onward use. The Authorised Network Model data elements have attributes such as type, subtype, rating, mounting and come from BAU sources of this information as described in Section 5.1 below.

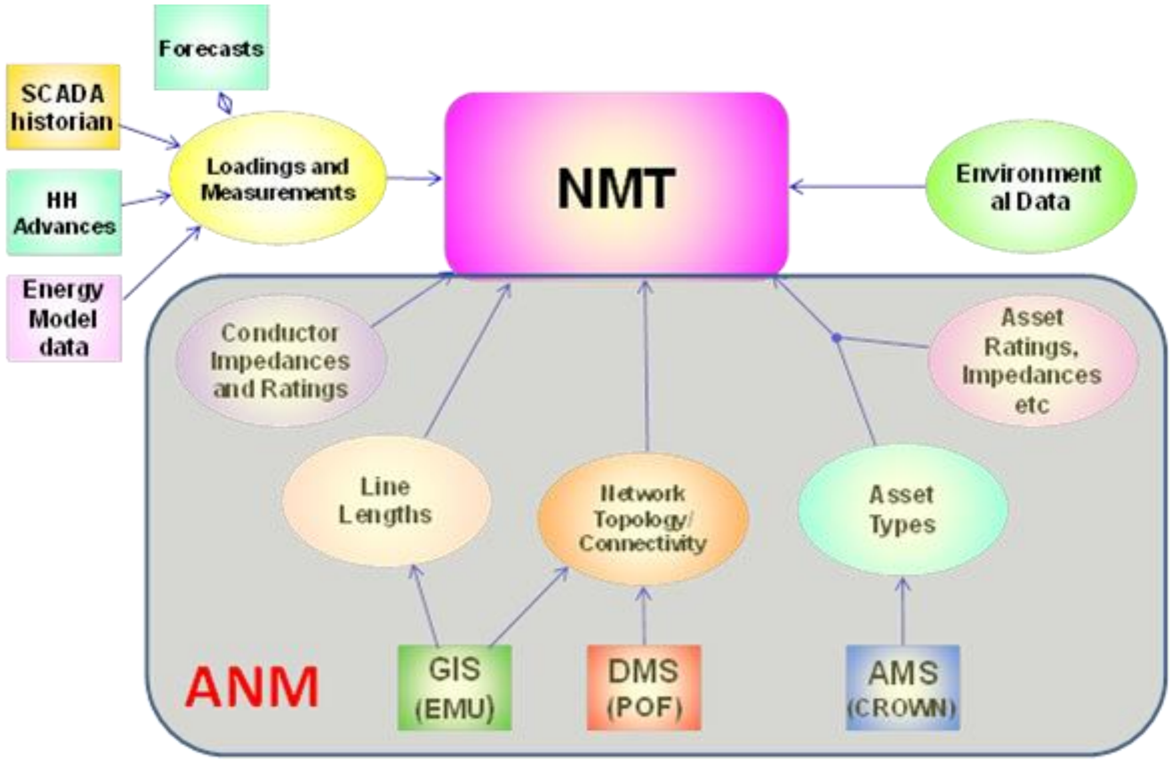
Each network node in the Authorised Network Model network representation, at which a load can be identified and quantified, is provided with a modelled load profile. These loads, which come from the Energy Model needed to be modelled as there is insufficient actual load data for the network as a whole. Load data derived from actual network monitoring corresponds to the time at which it was collected and can therefore only provide input for the starting point of the SIM analysis interval (real monitored data for future years is of course not available).

The initial pilot SIM only works on a small network area such as that most likely to be considered by an 11kV Planning User. The basic element in this respect is considered to be a Primary Substation.

5.1 Source Network Data for the Authorised Network Model

The diagram below gives a high-level view of the data sources used for the Authorised Network Model data, and its relationship to the other main datasets used by SIM. The Authorised Network Model dataset investigated and produced for the FALCON SIM has proved to be an effective prototype of an Integrated Network Model (INM) now under consideration for further implementation at WPD and which in general may be produced by combining data from three major DNO systems.

Figure 18: Authorised Network Model Data Sources



Source: FALCON Project

5.1.1 BAU Systems

Historically, DNOs have maintained different aspects of their network asset data in different systems, each specialised for a clearly focussed role, but with relatively little business justification for significant automated interfacing between these systems. A typical UK DNO's main systems that hold network asset data comprise:

- A Distribution Management System (DMS), integrated with SCADA, which supports the control rooms in operating the networks at HV and higher voltages, and often includes a tightly integrated Outage Management System (OMS) from the same product family which supports fault call handling and outage restoration and repair processes.
- A Geographical Information System (GIS), which holds the locations of all substation sites, poles/towers and underground cable joints as well as details of the routes and conductor types of the overhead lines and underground cables that connect these together to form the network.
- An Asset Management System (AMS), which holds records of the makes, models and ages of the physical assets that comprise the network together with condition information about each, and often including or integrated with a Work Management System that manages the inspections, maintenance and other work carried out on the assets.

In populating the network master data required by the SIM it was originally envisaged that the EMU GIS would to be the primary source of information. During the initial data analysis phase, however, it became readily apparent that:

- The EMU data on its own would not provide a sufficiently detailed dataset for SIM. In particular,
  - NMT needs to know which switchgear components are tele-controllable so it can make the correct CI/CML calculations, and
  - Technique models such as that for DAR needed additional nameplate information such as oil and fittings weights.
- Neither of the above are available from the EMU data.
- FALCON also populated electrical/thermal characteristics, such as line and component ratings and impedances, into the Power on Fusion (POF) system, where they were not already available, to support the technique trials. It was therefore necessary to match the EMU data to POF anyway in order to populate the available conductor type data against the line sections represented in POF.

It was therefore realised that the best approach would be to compile a common network topology dataset, now known as the Authorised Network Model (Authorised Network Model), and use this to populate the data required for the SIM.

An initial analysis of the electrical and thermal characteristics data available in POF and EMU also revealed a number of large gaps, and it was identified that the data held in the CROWN asset management system could fill some of these.

5.1.1.1 PowerOn Fusion

PowerOn Fusion (POF), formerly known as ENMAC, is the real-time control system used by WPD as their primary DMS and OMS. POF holds a detailed component/connectivity model that is shared by all of its modules, covering the network all the way down from 132kV to the isolation points immediately on the LV side of distribution transformers.

5.1.1.2 EMU

EMU is WPD's GIS, based on Bentley Microstation. It contains details of overhead line and underground cable routes and their conductor types. For each East Midlands site, it holds basic information on the type of site (e.g. distribution substation, pole-mounted auto recloser etc.) and a few characteristics of major components at the site. Site IDs are held against substation sites and new WPD pole numbers are populated against poles. These IDs are also populated onto the components at that site.

The major substation components are included in the East Midlands data because they were present in the former Central Networks *Smallworld* system, from whence this data was migrated. These components are not, however, present in the EMU datasets for the Wales and South West regions.

EMU is actually driven from a master GIS database, also held in Microstation files but not made directly available to most WPD users. For the East Midlands, where the major components at sites are held, the master diagrams have been modified to include geoschematic layouts around substation and significant pole sites so these components appear, when the site zoomed into at high resolution, to be connected in the appropriate arrangements.

WPD have also developed an extract process for providing network data from EMU in the DINIS External Data File (EDF) format. This provided a good starting point for building the geographical network model required for SIM. The DINIS extract removes straight-through joints, non-section and plain section poles (with no tee-offs or other equipment) from the source data and presents individual line or cable sections between each pair of sites. The EDF format is capable of encoding line or cable sections as groups of two or more spans where each span may have a different conductor type.

A tabular extract from the master dataset is also used to obtain ducting information. Because the DINIS extract was adopted first as the starting point for the data transformation process, and contains no internal IDs of features in the tabular extract, some re-matching has to be done to be able to populate the ducting information onto the cable spans extracted from the former.

5.1.1.3 CROWN

CROWN is WPD's AMS. It holds attribute characteristic data against both asset locations (sites, such as substations) and against individual items of equipment (transformers, switchgear, etc).

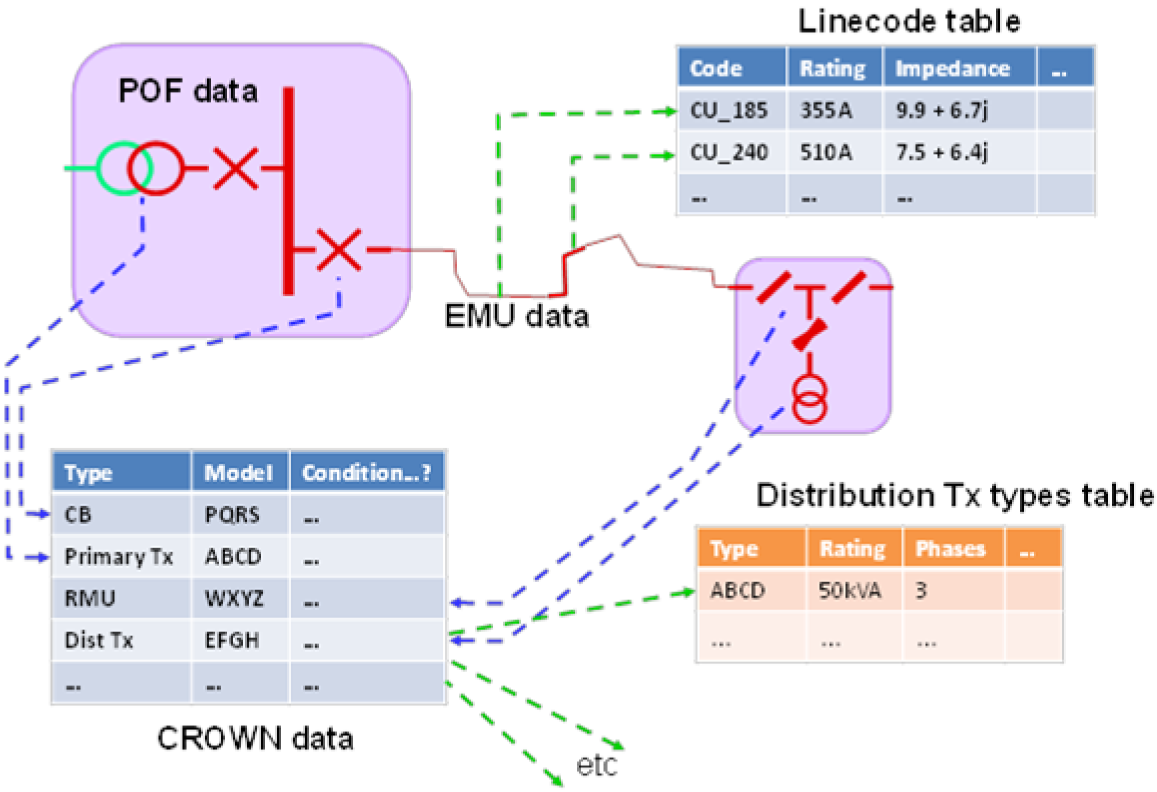
5.1.1.4 Ad-hoc Data

Several other key datasets were needed to populate the Authorised Network Model. These include tables of characteristic values for particular types of conductor, network asset, etc, and had to be compiled and maintained manually. In some cases this data was already available in a usable format within WPD: in others, it was necessary to compile this manually by the FALCON project team.

5.2 The Authorised Network Model Solution

The following diagram gives an overview of the structure of the resulting Authorised Network Model dataset

Figure 19: Overview of Authorised Network Model Dataset Structure



Source: FALCON Project

5.2.1 Authorised Network Model Compilation Process

A standard Extract-Transform-Load (ETL) process was devised to obtain the required source data, transform it into the formats needed by the FALCON systems, and then provide data which could be loaded into them. This process needed to be readily repeatable since the network is constantly evolving and thus the operational data sources (POF, EMU, CROWN) would also experience a level of ongoing change which would need to be able to be reflected in the Authorised Network Model in a repeatable manner so as to allow the SIM to retain an accurate source of network data.

The following basic conceptual approach was adopted for producing the Authorised Network Model dataset:

1. Match the POF and EMU network data by removing the elements of limited or no interest for modelling from each, then matching the sites remaining in the two datasets.
2. Match the significant POF equipment items, such as switch/fusegear and transformers, to their corresponding asset records from CROWN.
3. Use the available POF and CROWN attribute information for these items to determine their types and populate the relevant characteristics values.

The POF dataset is regarded by the business as the master database for network topology and normal switch states, as it is of necessity the highest quality 11kV topology dataset maintained by WPD. Once the decision to merge the datasets had been taken, it was therefore natural to regard the POF node-and-branch connectivity model as the definitive version of the network topology. This principle also ensures that a valid and consistent network topology is always produced. All that then happens if some part of a circuit can't be fully matched to the EMU data is that conductor types, ratings and impedances for those circuit sections, and map coordinates for some affected site locations, will be missing from the Authorised Network Model output. These do not prevent power flow and other modelling studies from being Run, but just reduce somewhat the accuracy of the results obtained.

The datasets, their description and sources are summarised in the following table.

Dataset	Description	Source(s)
Network topology	Switchgear components, transformers, cables, lines, fusegear, tee joints, tee poles etc with full connectivity information	EMU, POF
Cable characteristics	Electrical characteristics of cables eg impedances, ratings, cable diameters, lengths	POF, Linecodes table
Transformer characteristics	Electrical characteristics of transformers	POF, CROWN
Switchgear characteristics	Which components are protection devices, which are telecontrolled, etc	POF
Geographic diagram	Geographical locations of substations/sites and routes of cables/OHLs.	EMU
Terrain characteristics	Information to enable DAR models to compute wind effects on OHLs	Not required in this SIM

No weather station data is required for SIM as all its modelling is done for notional future dates for which no actual or even forecast weather data can exist. Where SIM technique models require meteorological inputs, these again have to be provided as tables/arrays of seasonal averages or extreme values associated to specific day types (with diurnal curves of values being supplied).

5.2.2 Matching POF and EMU Network Topologies

Matching sites, and the lines that connect them, between the POF and EMU datasets, was crucial to compiling the core skeleton of the Authorised Network Model.

For the purposes of this stage, the word “site” is generally used to mean any location where there is any significant network equipment that must be represented in both, thus embracing underground tee joint locations and any significant overhead pole/tower locations as well as substation sites.

Sites, such as substations, that have common keys between those systems were matched using those keys. Two inference rules were then applied to match most of the remainder.

The remaining anomalies were then investigated, and the matching completed by manually instructing the ETL process to remove items present only in one system or to manually match remaining sites.

Other than where the source datasets were inconsistent, about 96% of the sites were successfully matched automatically in this way. The remaining 4% were mostly accounted for by dead end spurs to pot ends which had been represented slightly differently between the source systems.

Some additional complexity was involved because the East Midlands data was still being converted from Central Networks to WPD standards, with different forms of site IDs still used in different systems.

5.2.2.1 Analysis of Area Core and Periphery

It was found to be necessary when considering the main FALCON network based on the six primary substations in the core FALCON area, that further substations on adjacent feeders had to be included in the Authorised Network Model due to the possibility that an intervention might attempt to (for example) transfer load to such an adjacent feeder. This meant that a core area of around 570 secondary substations had to be expanded by around a further 1170 to a total of around 1700 substations, a significant expansion in the data requirement for the Authorised Network Model.

5.2.2.2 I2F file conversion

The Authorised Network Model was translated from the database format where it was held following derivation into the IPSA internal I2F format for use within the SIM using an import process created by TNEI.

5.2.2.3 Display Representations

For the display coordinates to represent the network topology 'backbone' in terms of the nodes and branches that form the 11kV network, it was decided to use geographic coordinates to drive the IPSA displays, as these were readily available from EMU whereas POF's schematic diagram coordinates were not readily exportable.

5.2.3 Use of the IEC 61968/61970 Common Information Model

Use of the IEC 61968/61970 Common Information Model (CIM) for transferring the Authorised Network Model data between the compilation process and NMT was considered but decided against for the following reasons:

- None of the software products involved then supported it for what we needed; and
- It would have considerably increased the complexity and cost for the trials.

CIM support certainly would be an important feature for an industrialised version of our model compilation method to have.

5.3 Data Cleansing & Feedback to Operational System Source Databases

Asset data in any asset-managing organisation is never perfect, as the law of diminishing returns kicks in and the cost of achieving absolutely perfect quality data becomes unaffordable. WPD's East Midlands data is broadly fit for purpose for existing operational processes and requirements, but contains some detailed inconsistencies, data mismatches and minor inaccuracies, and different elements are mastered across different systems as noted above. For example some EMU pole location coordinates were found to be inaccurate by a few metres when compared with those obtained from a professionally conducted ground survey and other issues were identified as described in the following subsections.

The following table presents some high-level statistics on the size and quality of the FALCON trials network and the numbers of manual corrections needed to produce the Authorised Network Model dataset:

Item	Quantity	%
11kV feeders	103	
Feeders with unresolved topology discrepancies (after making the manual corrections below)	9	8.70%
Sites	2206	
Sites affected by manual topology corrections	91	4.10%
Nodes	6637	
Manual CROWN asset matches required	170	2.60%
Branches	6536	

5.3.1 Approach to Data Issue Resolution

It was expected that, as the data from the different sources were combined, discrepancies between different parts of the data and other discrepancies would be identified. So it made obvious sense to incorporate a system of detecting and logging these errors into the ETL process, and derive from this a dashboard showing the numbers of each main issue type found on each 11kV feeder.

The issues were then prioritised according to their impact on the FALCON project, including their implications for successful SIM operation, and steps taken to correct the most important types. Depending on the nature of each issue, and considering the most practical means of addressing it for FALCON, the data was then cleansed by one of the following means:

- Reporting erroneous data back to WPD data stewards who could then correct it in the source systems, so corrected data was obtained next time the ETL process was Run from end to end;

- Incorporating additional ETL logic to detect and auto-correct the discrepancies based on agreed business rules; or
- Incorporating correction tables into the ETL staging database and making the ETL process apply specific corrections as identified in these tables.

In a couple of cases where the nature of the issue involved unmatched records between two source systems (generally POF and CROWN), manual matching forms were developed to enable FALCON project members to match the offending records manually, with the resulting matches then being stored in an ETL correction table. This method was found to be particularly useful for matching POF switchgear and transformer components to their CROWN counterparts where these could not be matched automatically via their site locations and panel numbers.

The ETL conversion process also incorporated a table which listed and classified each 11kV feeder into one of three categories:

- FALCON trial feeders,
- Peripheral feeders – those immediately beyond a normally open point at the far end of a trial feeder, or
- Others – the remaining feeders from those primary substations outside the trial zones, with no NOPs shared with trial feeders.

Where data issues involved manual corrections of any type, the above information enabled the instances within the trial and peripheral zones to be rapidly identified so the project did not spend undue effort in correcting ones outside the area of interest. The feeder categories were also listed against each feeder on the data quality dashboard.

5.3.2 Issues Arising from the Timing of System Updates

It was recognised at the outset that the data obtained from POF would be more up to date than that from EMU or CROWN, because these are typically updated at different stages of the network change implementation process. In particular, the POF dataset has to be updated at the time each network change is commissioned, but the other systems are not typically updated until some time after the event.

Nevertheless, it was hoped the number of sites and circuits affected would be small, and in the August 2013 data baseline, discrepancies of this nature were found to appear on 8 out of the 103 circuits of interest to FALCON, though only in one case were more than three branches affected on the feeder in question. This was considered to be an acceptable level of data quality for FALCON because its main impact for SIM was only that accurate impedance and rating data could not be obtained for the mismatched topology branches. As expected, this was found to be the single largest reason for cases where the network topology between sites could not be fully matched between POF and EMU.

5.3.3 Electrical and Thermal Characteristics Data

An important element of the Authorised Network Model is the electrical and thermal characteristic data that describes the properties of the individual network assets.

Sufficient characteristics data was sought to fulfil the needs of the different types of modelling study that NMT would need to execute, which comprise

- Power flow studies;
- Network reliability studies (i.e. CI/CML forecasting); and
- Fault level studies (though these were later descoped as described in +++ above).

For conductors, some branches had individual rating values (but no impedances) available in POF, whilst impedances and ratings for most lines successfully matched to EMU could be obtained from a conductor catalogue indexed by the EMU conductor type. (A small number of conductor data types did not have matching entries in the catalogue dataset.)

For switchgear, ratings were available in POF and, if the component in connection was successfully matched to CROWN, its model information from there could also be used to obtain these.

For transformers, their power ratings were readily available in POF but a type catalogue had to be constructed to provide other characteristics such as impedances and iron losses.

When all the data had been assembled, a number of discrepancies were found between the different sources, particularly as regards ratings, where different datasets had different types of rating (normal, cyclic, winter, summer, spring/autumn, etc). At the time when this was done, it was clear that more analysis would be required to fully understand these discrepancies but the impacts of some errors in these characteristics was not understood. It was therefore decided to make all of the different rating values available to NMT within the Authorised Network Model so that these could be selected as required for Running SIM models and the selections refined, if need be, after experience from Running the models had been obtained.

5.3.4 Linkage to Load Data from the Authorised Network Model

The POF network topology data contained accurate records of all the distribution substation transformers and HV customers fed from the trial zone network. But when these were compared with the initial list of load points being used to prepare the Energy Model, a number of omissions from the latter, including IDNO outfeeds and all of the HV customers, were rapidly identified. Further work then had to be done to obtain the required load profiles for these additional points.

16 locations were also found in the main FALCON trials area in Milton Keynes where multiple transformers were deployed. This presented a problem because IPSA models these as individual components whereas the Energy Model component generates load profiles at substation level rather than per transformer. This situation therefore needed to be handled in the SIM, which was achieved by IPSA assuming that the load was split between the two transformers joined by a token busbar.

5.3.5 Accuracy and Completeness of Data

Many assets on the network pre-date the systems currently used to track and manage them and not all necessary attributes required for full accurate modelling are known in detail. Some deployed transformer types are no longer current and their operating characteristics can be different to assumed limits and specifications. There are also significant difficulties with the completeness of records held in respect of underground cables where depth of burial, means of burial, soil type, proximity to other cables or objects was simply not recorded and could in some instances never be known completely at all points.

Combined with the other types of data issue described above, this clearly places limits on the accuracy and completeness of the Authorised Network Model dataset. The impact of these limitations, particularly in terms of the relative errors in the modelling results that result from them, bear further investigation and additional research in this area would be particularly useful.

For example, missing impedance data for a small percentage of the conductors on an 11kV feeder are only likely to make a small percentage difference to the results from a powerflow or fault level study, and this small error may be dwarfed by other limitations in the modelling dataset such as inaccurate load profiles or inaccurate modelling of unmetered supplies such as street furniture. If the percentage errors attributable to each of the potential causes could be estimate then it would become much clearer which data most urgently warrants refining.

Perfect quality asset data is always unaffordable, and data quality must always be driven by justified business needs.

5.4 Modelling Constraints from Data Availability Limitations

The data that could readily be populated into the Authorised Network Model was significantly constrained by that available in the source systems or in readily available reference tables such as conductor type catalogues. The current Authorised Network Model scope is limited to the most important network attributes required for traditional modelling study types such as power flow, network reliability and fault level studies.

This presented a number of limitations in the extent to which SIM/NMT was able to accurately model the smart intervention techniques. The advanced (smart grid) modelling deployed within the SIM points the way to a potential need for additional, wider information requirements to cover the additional factors pertaining to the network area as a whole and individual deployments in particular. These additional data requirements will almost certainly include:

- Average (not real-time) weather conditions – ambient temperatures (for DAR thermal modelling), wind speed, amount of sunlight usually falling in a given season/time of day;
- Accommodation conditions for certain key equipment so as to facilitate more accurate modelling of these assets;

- Soil type and moisture content/water table levels allowing for the environment of buried cables to be modelled as accurately as possible;
- Underground cable deployment details (depth of burial, conduit used or not, proximity of other cables etc.);
- Proximity of customers of different types (which could affect choices for battery placement where noise nuisance may be a consideration for deployment decisions);
- Additional equipment details not currently held for certain types of equipment and required by computational algorithms for the advanced techniques such as DAR (see below);
- Network locations for sites/users with DG capabilities and associated details.

A further consideration here is that actual values for many of these new attributes cannot readily be obtained (if at all) without the DNO investing significant effort and incurring cost, so the value of this information to the modelling would need to be determined before embarking on any extended data gathering/improvement exercise

5.4.1 DAR Technique Modelling Requirements

A number of additional and very specific thermal characteristics of transformers, such as the core, oil and fittings weights, are needed by the DAR technique modelling. No data could readily be found when FALCON sought to fill in these details in the list of transformer type characteristics as inputs to the SIM modelling of the technique. The fields for these parameters could not therefore be populated in the characteristics tables. This can always be done at a later stage if/when it becomes possible to obtain the required information, though (again and as noted above) the level of effort and thus the cost required to support such a data gathering exercise is not trivial and in some cases it may not even be possible for older units. For the initial pilot SIM, the project therefore needed to take the pragmatic approach and apply a number of default values for the SIM DAR technique models.

5.4.1.1 Cable Modelling

The thermal conductivity/resistivity of the surrounding soil plays an important role in determining how much current can be carried by an underground cable when dynamic rating of the cable can be applied. The faster the soil can dissipate the heat generated by the cables I^2R power loss, the higher the current that can be delivered.

5.5 Conclusions

The project recognised in good time that the diverse nature of the source databases meant that these needed to be processed to present a single derived, unified view of this data for the SIM. The actual source systems or databases could not have been accessed directly by the proof of concept SIM itself anyway.

The existing network data is broadly fit-for-purpose for traditional DNO operations but would require improvement to support widespread deployment of Smart Grid/Low Carbon technologies and techniques.

Recognising that there is significant room for improving the overall DNO network database landscape, the production of an Integrated Network Model has been flagged as a highly desirable strategic goal.

The approach of combining data from the three main systems was very successful and was achieved within budget and timescales, despite the datasets still being in a transient state of conversion from using Central Networks' former data keying standards to those of WPD. The approach used could readily be industrialised and scaled up to entire DNO regions to provide high-quality modelling data and CIM interoperability:

- This would also provide a good platform on which to base a Master Data Management solution for Network data, supporting data governance processes and driving out gradual but sustained data quality improvements.
- It only entails relatively low impacts on existing BAU network master systems (DMS/GIS/AMS).

Several additional datasets will be needed for Smart Grids, and these will also need to be appropriately managed and maintained within the overall Data Architecture. A better understanding of which data items the relevant modelling techniques are most sensitive to errors in is needed to identify which data aspects are worth investing in improvements to. Further research into this area would be valuable.

SECTION 6

SIM RUN Analysis

The flexibility of the SIM means that huge numbers of scenarios, representing widely different approaches to a number of assumed prevailing conditions and network evolutions, can be investigated. The ones chosen for presentation in the FALCON Final Report are merely the tip of the iceberg, being an exploration, in the limited time available, of a small set of these Experiments (SIM Runs). The Experiments that have been explored cover various aspects of network evolution as well as exploring facets of the SIM itself, including various customer behaviours in response to postulated conditions and costs and various network adjustments. Further and much more extensive scenario plotting and results analysis can be expected to yield further conclusions, and work is now continuing on the further development of the SIM beyond the initial prototype outside the scope of the FALCON project.

The investigative work has taken the form of three main strands:

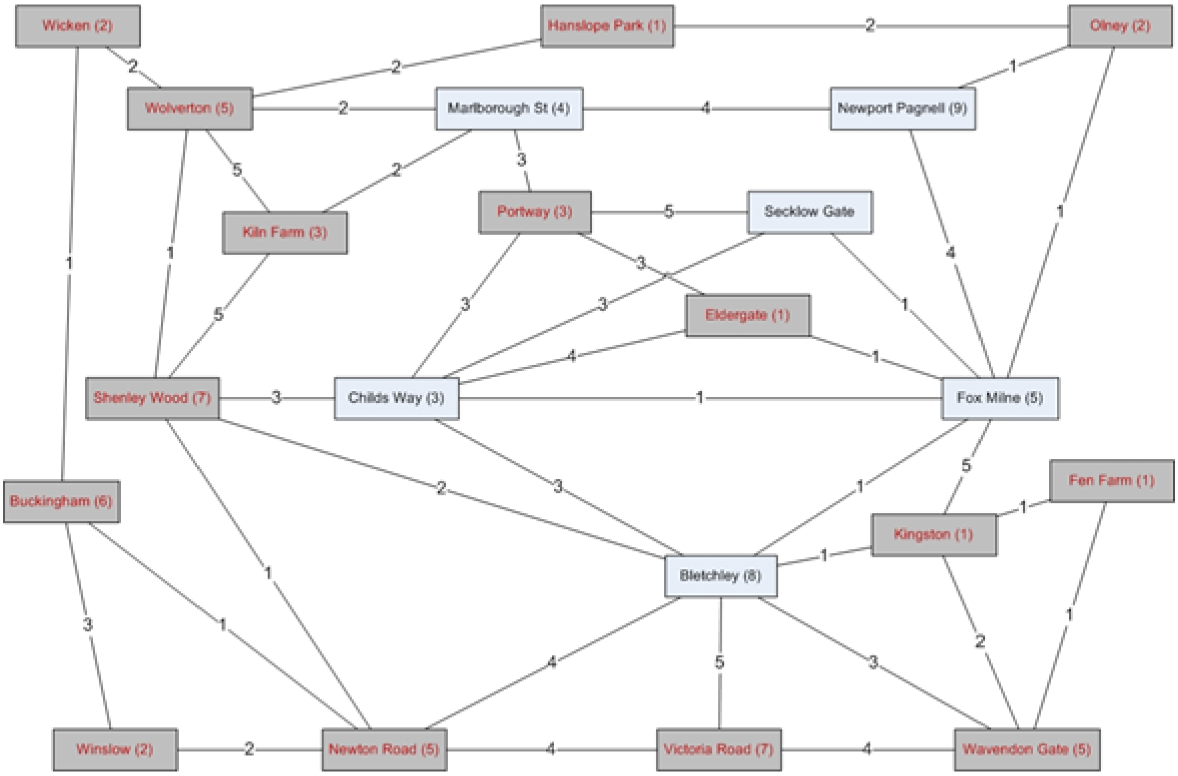
- Initial Investigation Runs exploring the SIM capabilities and validating the results;
- 11KV Planner oriented Runs targeted at obtaining operating feedback as well as network insight following exposure of 11kV planners to the tool;
- Strategic Investigation Runs systematically exploring the target network and the capabilities and limitations of the SIM over the full simulation horizon (to 2050).

Compared to the strategic investigation Runs, the 11KV Planner oriented experiments are targeted at a smaller network area (within a single primary) and over a short time frame, typically five years. The Strategic Runs focus on multiple Primaries as well as a much longer evaluation time frame.

6.1 The Network Area Under Analysis

The FALCON trials area of Milton Keynes comprises a core six primary substations and a peripheral network area which must be considered alongside the core area to provide the adjacent feeders required for N-1 analysis and to provide options for ALT and Mesh techniques. The network is a mix of business premises, domestic sites and commercial properties served by mainly underground cables with one Primary area (Secklow Gate) atypical by being mainly commercial properties. The extended network area is shown schematically in the diagram below:

Figure 20: Primary Interconnects from Authorised Network Model Data



Source: FALCON Project

Looking at this diagram it is readily seen that the number of feeder interconnects for the core six Primary substations are as listed in the table below:

Table 5: Core Primary Substation Characteristics

Primary	Feeders	Secondary Substations	Secondary Subs with FALCON LVM
Marlborough St	11	68	16
Newport Pagnell	9	77	23
Secklow Gate	9	13	0
Fox Milne	13	54	26
Childs Way	17	59	8
Bletchley	19	97	39

Source: FALCON Project Authorised Network Model

The following table lists the secondary substations with FALCON LVM monitoring capability, by primary grouping, in case this facility is useful for checking future load evolution projections used during FALCON. Such a validation exercise is not currently planned but could be considered.

Table 6: Core Primary Substations with LVM Capability

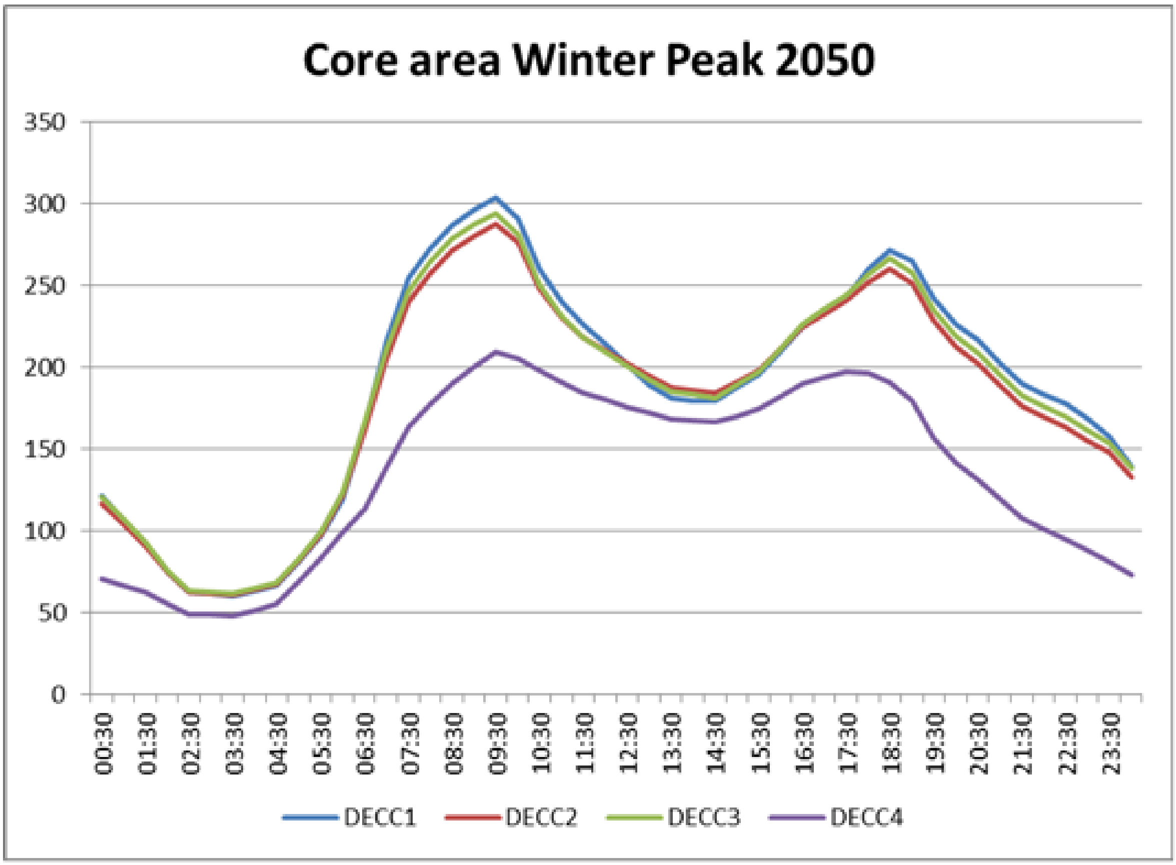
Primary	Substations with LVM
Marlborough St	Malins Gate, Kents Road Stantonbury, Unit 32 Blundells Road Bradville, Glazier Drive Neath Hill, Rainsborough Giffard Park, Sports Arena Stantonbury, Stantonbury Chestnuts, Kingsfold Bradville, Bradville, Crispin Road Bradville, Mercers Drive Bradville, Nightingale Crescent Bradville, Burnett Stantonbury, Myrtle Bank Stacey Bushes, Temple Stantonbury, Tower Drive Neath Hill
Newport Pagnell	Richmond Way Newport Pagnell, Church End Lathbury, St Johns Street Newport Pagnell, Riverside Park Estate Newport Pagnell, Bury Lawns Newport Pagnell, Queens Avenue Newport Pagnell, Broad Street Newport Pagnell, Newport Pagnell Local, Broad Street Flats Newport Pagnell, Red House Newport Pagnell, Westbury Lane Newport Pagnell, Portfield Road Newport Pagnell, Lakes Lane Newport Pagnell, Cypress Newport Pagnell, Caldecote Mill, London Road Ind Newport Pagnell, Wepener Farm, 7 Tanners Dr Blakelands, Landsborough Gate Milton Keynes, Granvills Square Milton Keynes, Willen Road St Ltg, Crawley Road Newport Pagnell, Leary Crescent Newport Pagnell
Secklow Gate	None
Fox Milne	Griffith Gate Middleton, Swanwick Walk, Worrelle Avenue Middleton, FALCON Avenue Springfield, Chadds Lane No2 Peartree Bridge, Noon Layer Drive West, Perran Avenue Fishermead, Noon Layer Drive, Ambridge Grove, Helford Place Fishermead, Buckingham Gate Eaglestone, AWA Pumping Station Middleton, Stamford Avenue Springfield, Butterfield Close Woolstone, Swanwick Lane Broughton, Brooklands Farm Cottages Broughton, Broughton Combined School, Broughton Village, Broughton Weighbridge, Broughton Milton Keynes, Moulsoe Church, Thorneycroft Lane Downhead Park, Finch Close Milton Keynes Village, Walton Road Middleton, Blanchland Circle Monkston, Parneleys Milton Keynes Village
Childs Way	Talland Ave Fishermead, Mansell Close Shenley Church End, Ashpole Furlong East Loughton, South 5th Street CMK, South 9th Street CMK, Grace Avenue Oldbrook, Boycott Avenue Oldbrook, The Oval Oldbrook
Bletchley	Taunton Deane Emerson Valley, Perracombe Furzton, Blackmoor Gate Furzton, Kinross Drive Bletchley, Parkside Furzton, Caithness Court Bletchley, The Linx Bletchley, Spenlow Road Bletchley, Bean Hill Neapland, Barnfield Drive East Netherfield, Barnfield Drive West Netherfield, Old Groveway Simpson, Wraxall Way Ashlands, Bletchley Park Area A, Rickley Lane Bletchley, Dorchester Avenue Bletchley, Neath Cresent Bletchley, Middlesex Drive Bletchley, Westminster Drive Bletchley, Buckfast Avenue Bletchley, Surrey Road Bletchley, Archers Wells, Beaverbrook Ct Bletchley, Dumfries Close, Sussex Road Bletchley, Angus Drive Bletchley, Hertford Place Bletchley, Whalley Drive, Buckland Drive West Netherfield, Bean Hill Lammas, Marram Close Beanhill, Chapter Coffee Hall, Jonathans Coffee Hall, Wheatcroft Close Beanhill, Helford Place South Fishermead, Sir Frank Markham School, Downdean Eaglestone, Jamaica Coffee Hall, Granby Court

Source: FALCON Project Authorised Network Model

6.1.1 Load Evolution

The FALCON Project element that dealt with future load profile generation was the *Load Estimation* workstream for which a separate FALCON report is available. This section includes some typical load profile curves by way of an illustration of the form of these and to show how they evolve over the modelled time interval (to 2050).

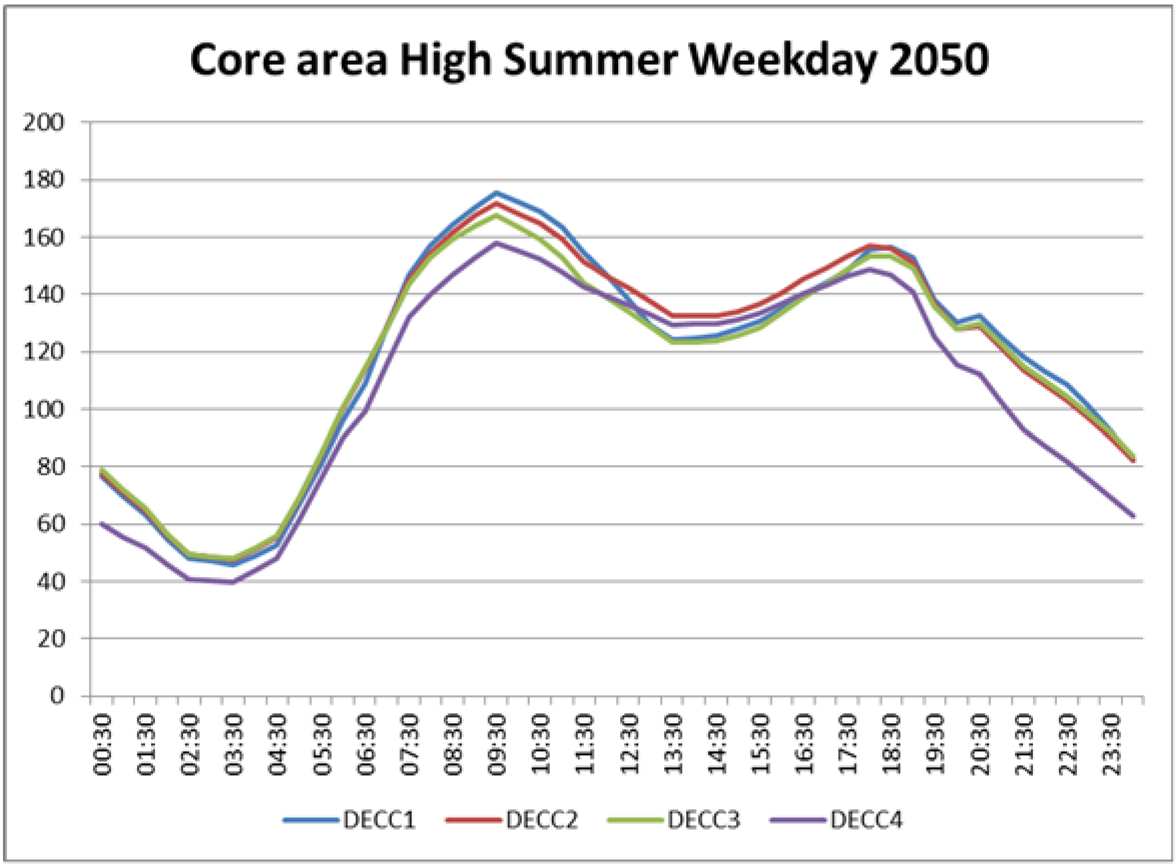
Figure 21: Peak Characteristic Day - Corrected Values



Source: Falcon Load Data

The figure above shows the four DECC scenario predictions for the Winter Peak Day type in the final simulation year 2050. This illustrates that DECC4 is the least onerous demand scenario for such days, with much reduced peaks and a slightly lower midday dip, while the other three demand scenarios are broadly similar with DECC1 being the most onerous of all. This may be contrasted with the plot below for the High Summer day type, where all four demand scenarios are more closely aligned (though again, DECC4 is the least onerous overall).

Figure 22: All Scenarios (DECC 1 - 4) High Summer Weekday Characteristic Day - Corrected Values

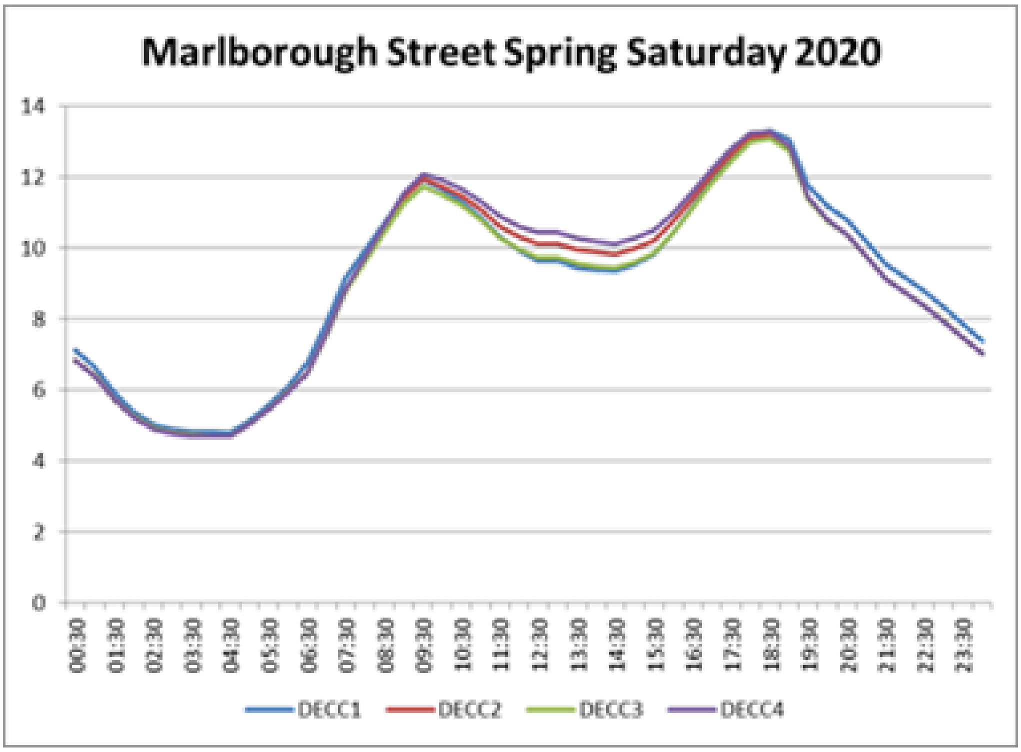


Source: FALCON Load Data

Looking at a single primary, Marlborough Street, the divergence between the load profiles for different scenarios can be seen to develop over time.

In 2020 the differences between the profiles are relatively small.

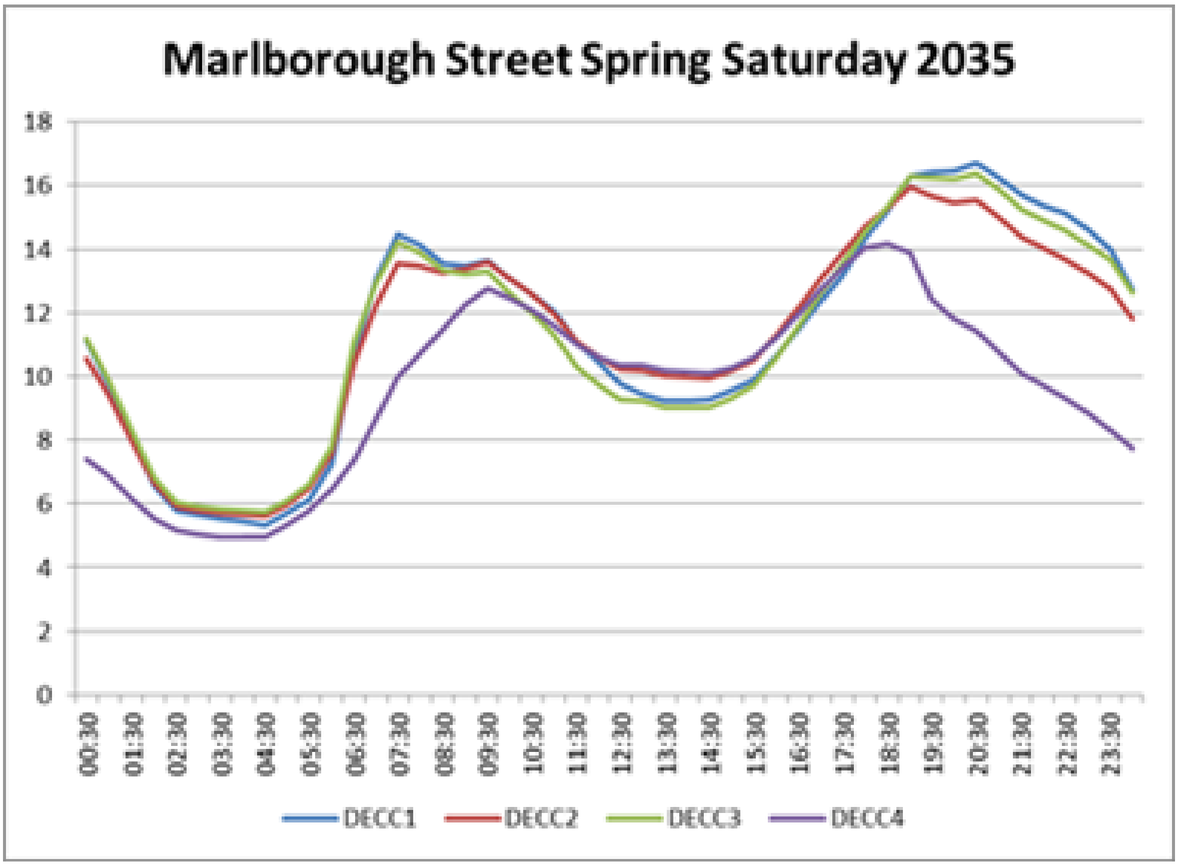
Figure 23: Marlborough Street Spring Saturday Profiles



Source: FALCON Load Data

By 2035 differences between DECC4 and the other scenarios at peak times are more apparent.

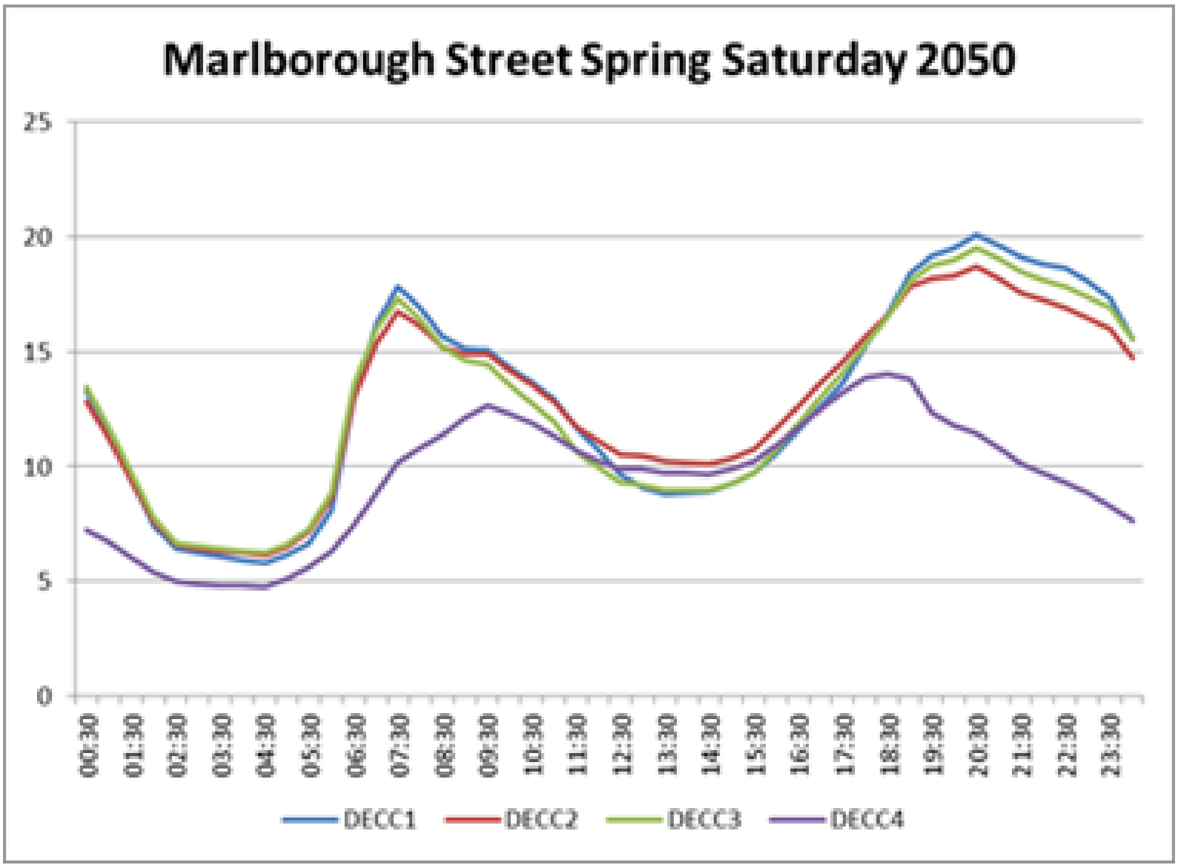
Figure 24: Marlborough Street Spring Saturday 2035



Source: FALCON Load Data

By 2050 the difference between DECC4 and other scenarios has increased further.

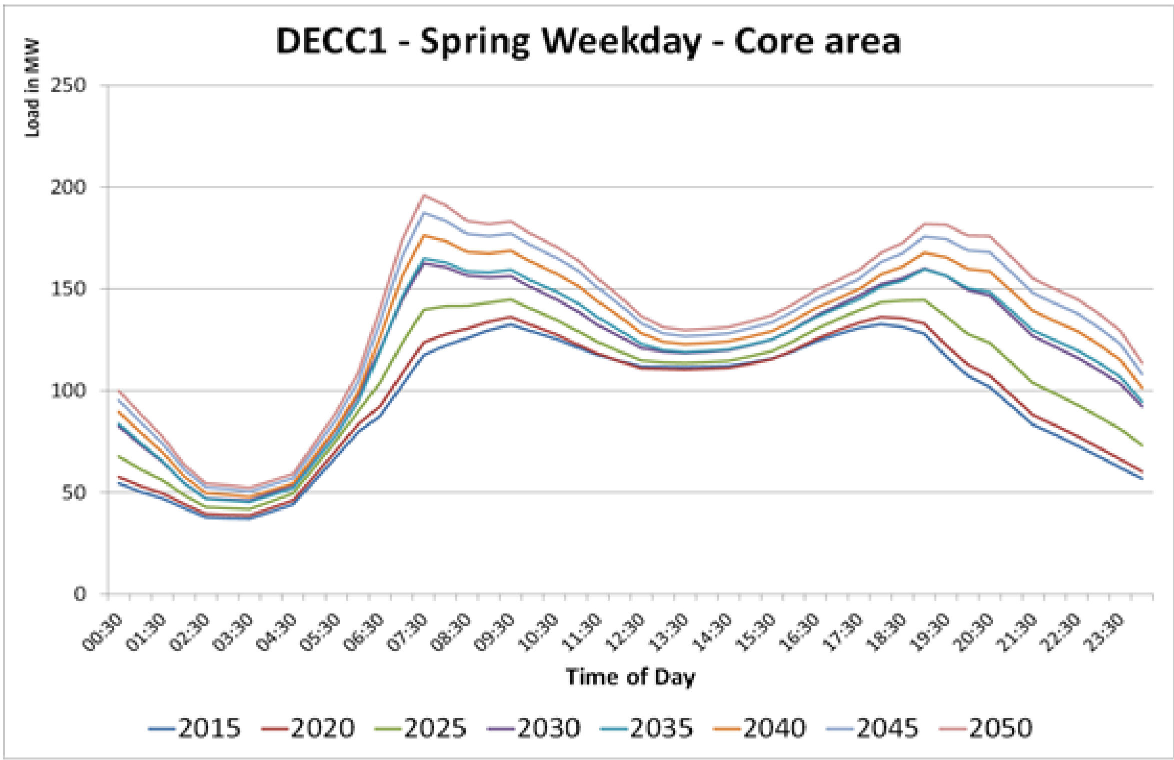
Figure 25: Marlborough Street Spring Saturday 2050



Source: FALCON Load Data

The following plot shows a different view – being the evolution of DECC1 based load profiles at 5 year intervals out to 2050 (for the Spring Weekday characteristic day type).

Figure 26: Load Evolution, DECC1 - 5 year Intervals to 2050



Source: FALCON Load Data

6.1.2 Load Data Adjustments at Import

It was determined during SIM integration and validation testing that it was desirable to be able to implement a capability to apply changes to the input load profiles coming from the Energy Model for a number of reasons. These included over and under estimates, in certain substation types, for which a standard base offset would ideally be applied to correct for this shortcoming in the Energy Model. In addition it was found that for DSM an additional adjustment mechanism would allow for reflecting of the inclusion of generalised DSM in the base loads.

An import script modification mechanism was therefore included in the SIM that allowed for the definition of:

1. Introduction of standard adjustment values for selected loads;
2. Peak periods that load will be transferred from for DSM;
3. The amount of the load will be transferred from each period as a percentage of the load in that period (DSM);
4. The periods into which the load will be transferred (DSM);
5. The split of the total load to be transferred which will be allocated to each half hour – these will all add to 100% (again DSM).

In an added complexity it was also decided to allow for different parameters for different years as greater flexibility could be expected to be required towards 2050 when a higher proportion of the load is expected to be controllable (EVs and Heat Pumps).

An additional software feature was also added to the SIM itself so as to allow for the different treatment of year 1 during the execution of the SIM analysis. If selected, year 1 may be managed using traditional reinforcement only to patch the network in this initial year.

6.2 Background to the FALCON 11kV Planner Run Set

This document has described previously how the SIM has two main groups of business users, namely the 11kV Planners and Strategic Planners. The mode of usage of the former is explored in a number of initial Runs as described in this section. In regard to the latter, the Strategic Users, the Runs supporting this are described in the section following.

11kV Planners are expected to use the SIM to plan work on a specific very localised area of the network performing short-term (typically up to 5 years forward) analysis of the effects of change and to model evolution of the network in that area under a range of prevailing conditions – specifically under the impact of different demand scenarios and with or without the inclusion of patches representing potential developments. This is expected to allow the Planners to view the worst (and best) case scenarios, get a view on costs (and the ranges of these) and assess the relative merits of different intervention strategies. The SIM was therefore used to carry out a number of Runs for six of the FALCON Primary Substations over a five-year period in the FALCON Project study area. This 5-year period is characteristic of the short-term view that would be taken by a planning engineer to inform the production of an 11kV reinforcement programme or as a preliminary study prior to a new load connection being carried out. To produce a range of potential load growth options the Department of Energy & Climate Change (DECC) energy demand scenarios have been used – load profile data sets for all primary and secondary substations in the trials area are available under these various DECC demand scenarios.

The SIM RUN set used for this analysis is summarised below.

Table 7: 11kV Planner Experiment RUN Set (All runs were from 2015 to 2020 using A star search)

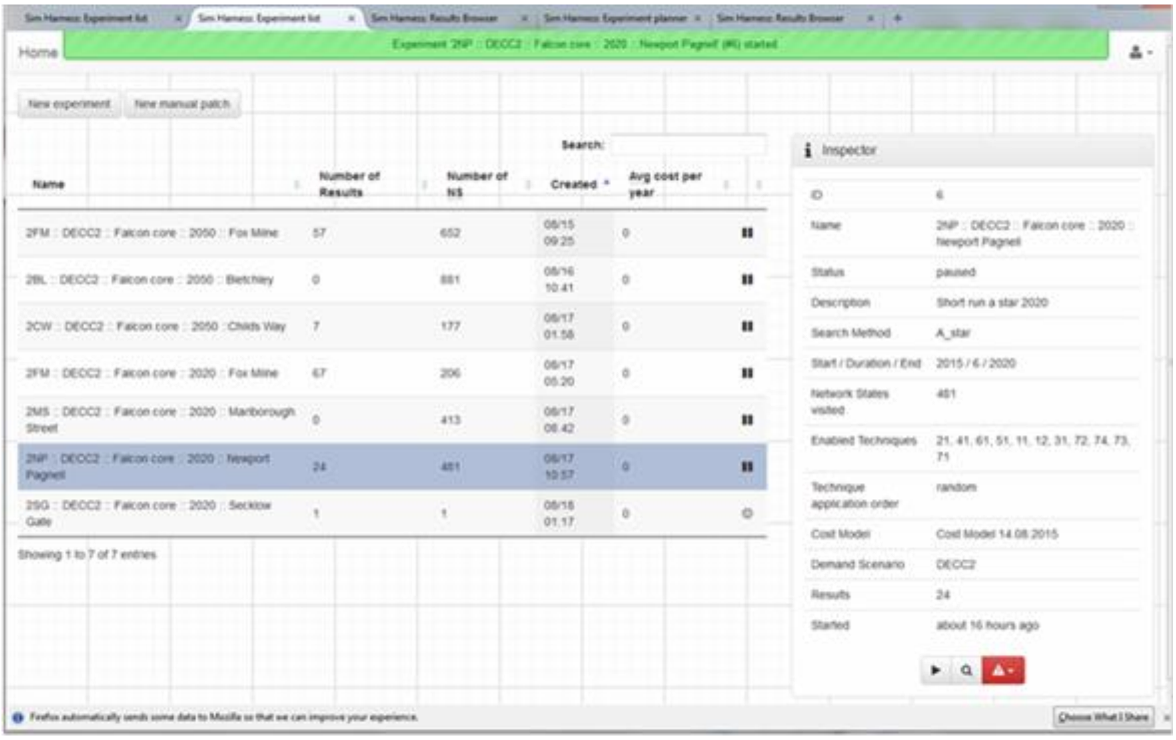
RUN No	Network Area	Experiment Details	Number of Network States and Results
A	Newport Pagnell	DECC3 Traditional Reinforcement only	R=32 NS=629
B	Newport Pagnell	DECC 3 all techniques	R=16 NS=356
D	Fox Milne	DECC3 Traditional Reinforcement only	R=81 NS=634
E	Fox Milne	DECC4 all techniques	R=112 NS=287

RUN No	Network Area	Experiment Details	Number of Network States and Results
F			
G	Bletchley	DECC1 Traditional reinforcement only	R=12 NS=369
H	Bletchley	DECC2 all techniques, (73&74 enabled in 2015)	

Source: FALCON Project

The SIM Experiment Manager main screen covering these Runs is also illustrated in figure 27 below. Note that the RUN detail inspector to the right of the window shows the details for the highlighted RUN for Newport Pagnell Primary.

Figure 27: 11kv Planner Analysis RUNs



Source: FALCON Project - SIM Experiment Planner Main Screen

The SIM outputs and subsequent additional analysis from these Runs included:

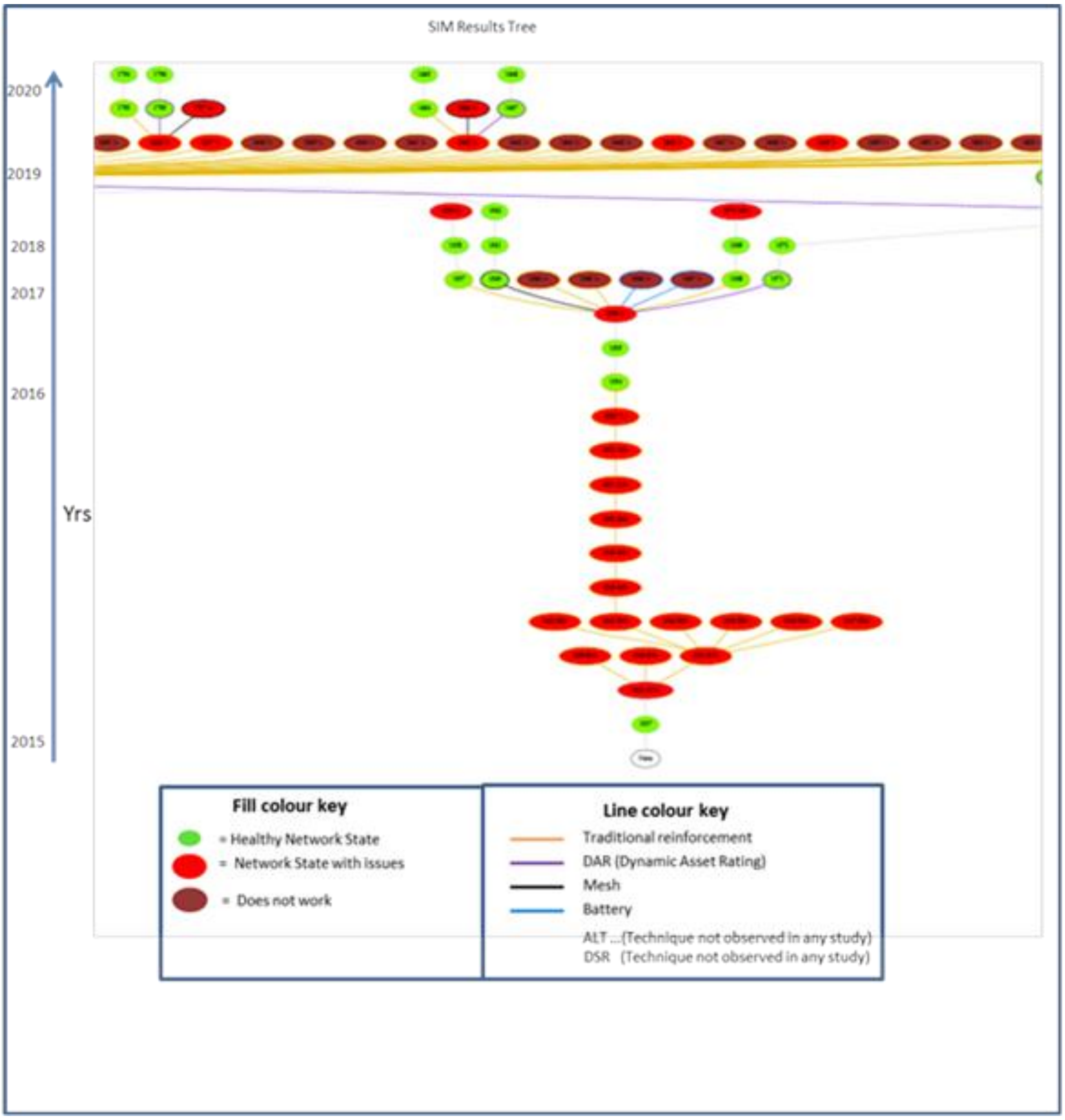
- The provision of lists of interventions/patches applied by year – as a function of the demand scenario in use;
- The costs of the interventions carried out in each case;
- The characteristic days on which failures occur;
- A view from the Planners on the usability of the SIM software, the ability of the user to analyse the results and see what is happening and recommendations for further SIM enhancements.

- On the third point, possession of this information will potentially allow better tuning of the SIM itself if the set of characteristic days in use can be effectively reduced as a result of this analysis.

6.2.1 Interacting with and Analysing Actual SIM RUN Outputs

- The results from the SIM can be viewed in a number of ways using both SIM provided and additional tools. For the 11kV Planner studies, a good visual representation of the Runs can be viewed in a SIM Results Tree (balloon diagram) created by the SIM Inspector.
- The SIM result tree diagrams are displayed as HTML documents and can be viewed in a web browser (Firefox is the browser specified for the SIM). Standard settings in Firefox have some flexibility in zooming and navigating to particular areas of interest chosen for examination. Because of the size of the output diagram, it is not practical to display or print this in its entirety as a relatively straightforward study for a five-year period produces an output with many hundreds of steps. It is considered important for future development that ways are explored to reduce or simplify the view in order to allow the user to focus on the more relevant branches and elements.
- It is also noted that attention to the careful setting of certain parameters and thresholds before each RUN would reduce the amount of output and enable the planner to focus on the more important issues. An extract of a view for the DECC1 scenario is shown below.

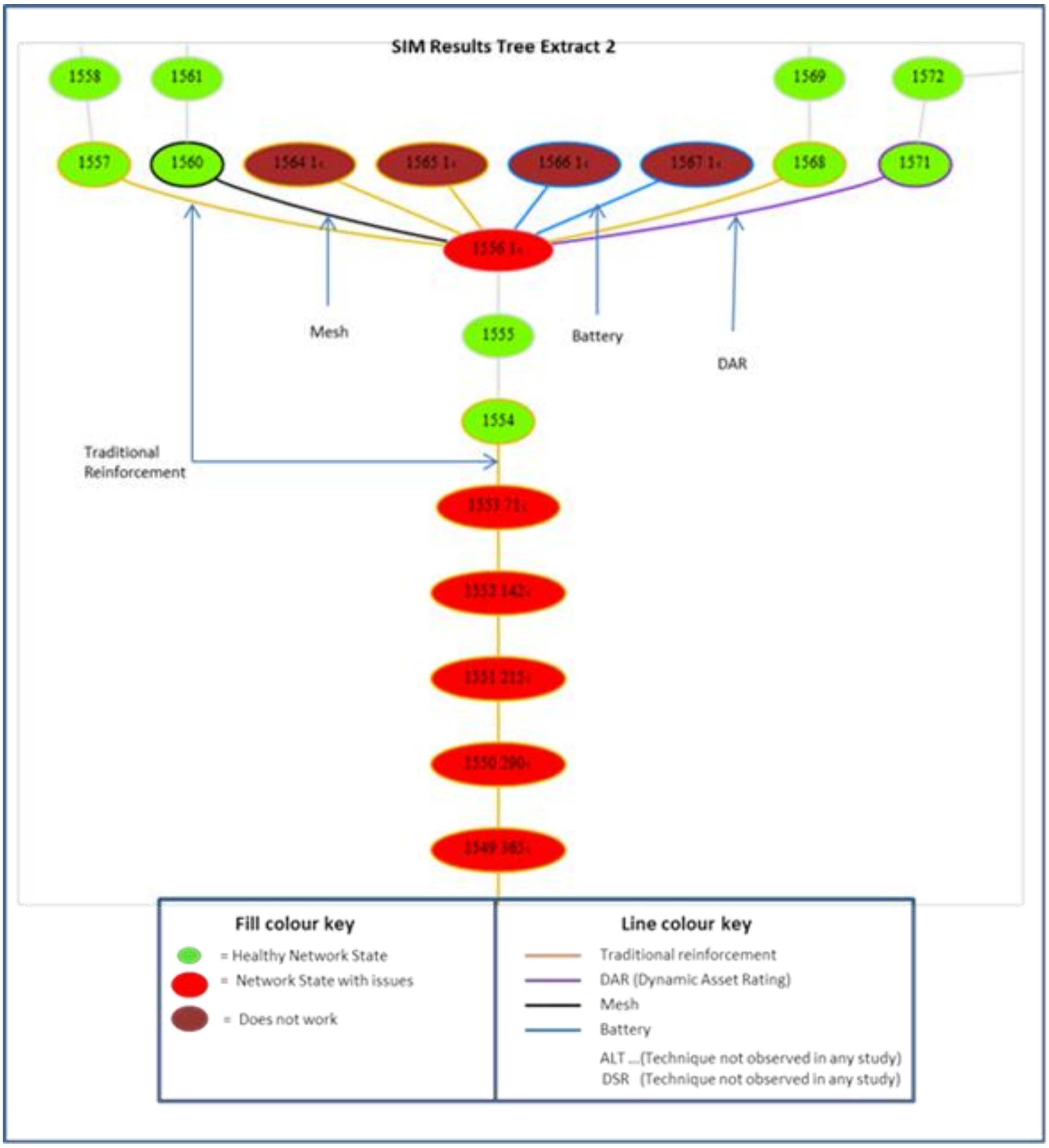
Figure 28: Extract from a SIM Results Tree



Source: FALCON Project Data Analysis Tools

The user may zoom into the results diagram and this allows the individual process steps to be examined in more detail. By observing the line colours (both connections and borders) it can be clearly seen which technique has been applied to arrive at each step. The "balloons" each represent an individual network state evaluated by the SIM (and whose unique identifying number is shown on the diagram, along with the number of issues remaining), and these states are either fixed/healthy, failed (with issues) or invalid. The network state number can be used to show an annotated zoom of one of the state evolution trees, as illustrated below, and this details how the techniques and other details are presented for viewing and analysis.

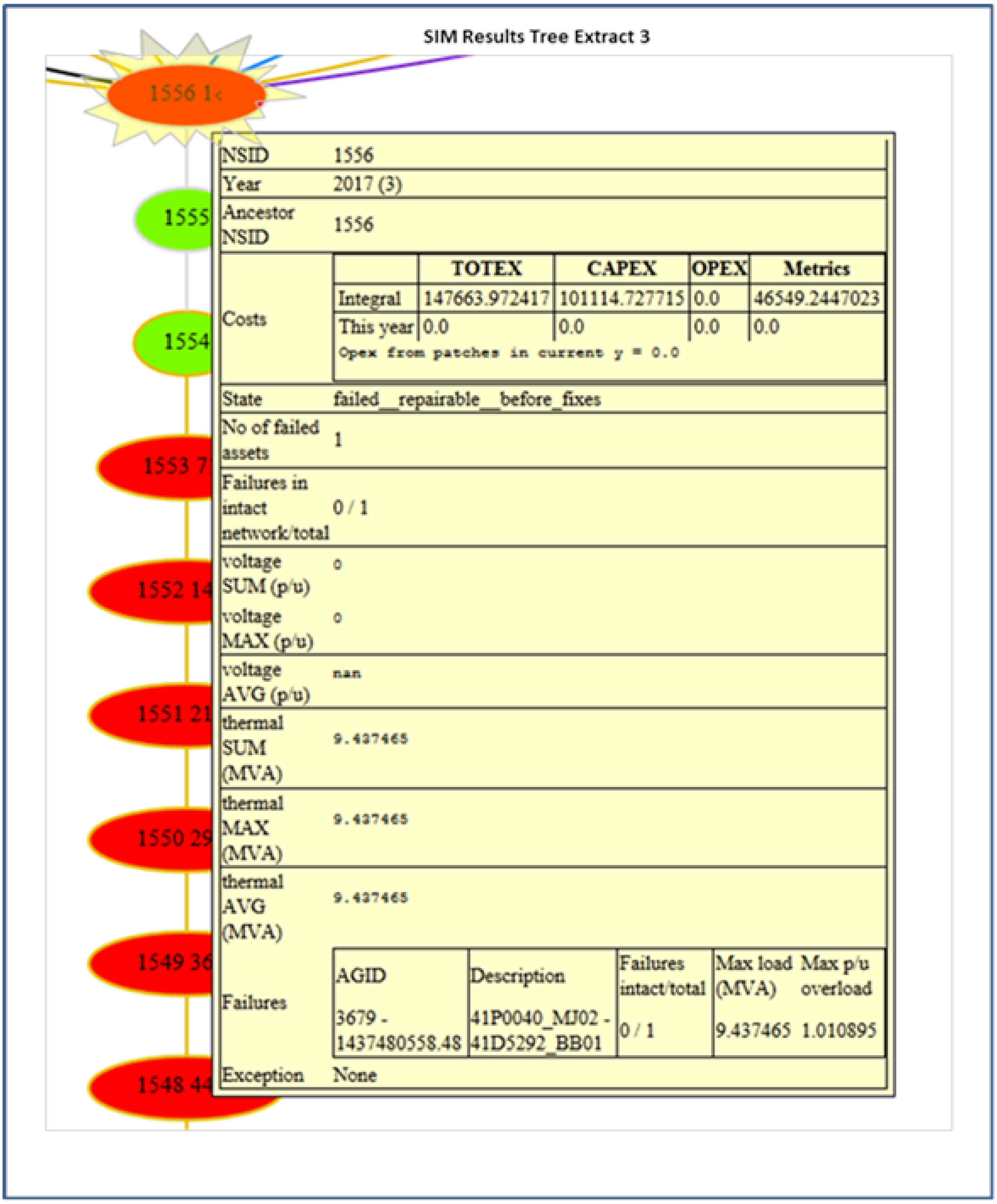
Figure 29: SIM Result Tree (Zoom)



Source: FALCON Project Data Analysis Tools

By selecting any network state with the mouse, the details of that step can be displayed in a pop up window, which makes it easy to step through and understand the progress of the study. This is illustrated below;

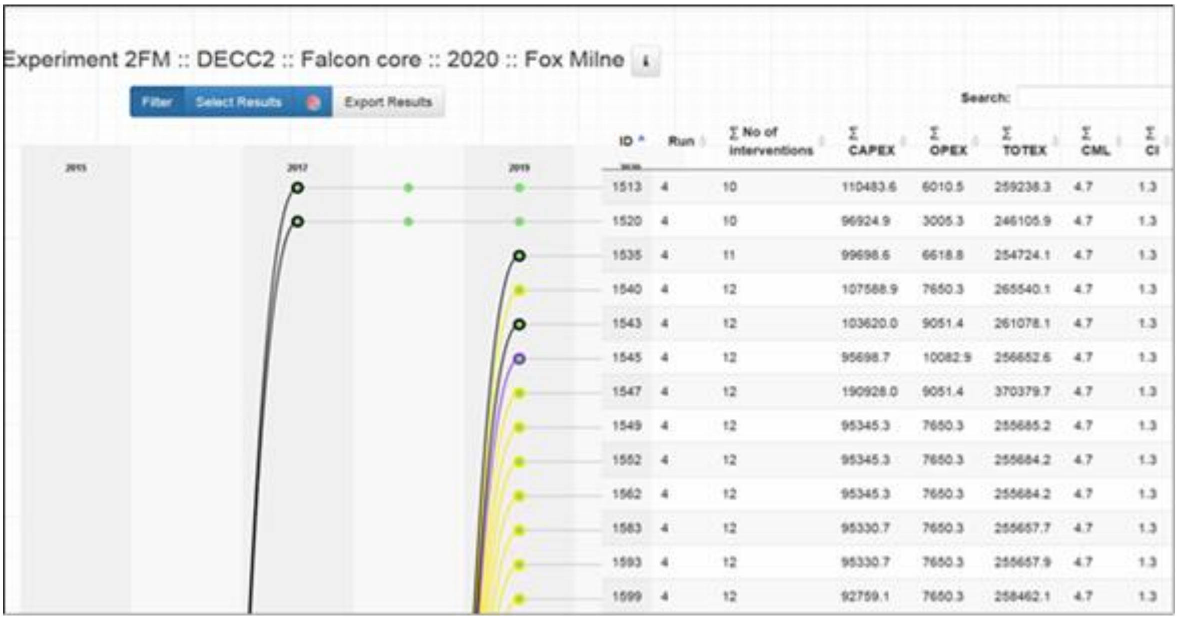
Figure 30: SIM Network State Detail Expansion



Source: FALCON Project Data Analysis Tools

Inside the SIM itself (using on-board functionality) Run results can also be viewed in a Results Browser view. This facility allows the results to be selected and viewed in a number of different orders. This can help the user with the selection of particular results although again the sheer number of results often means that this is not straightforward.

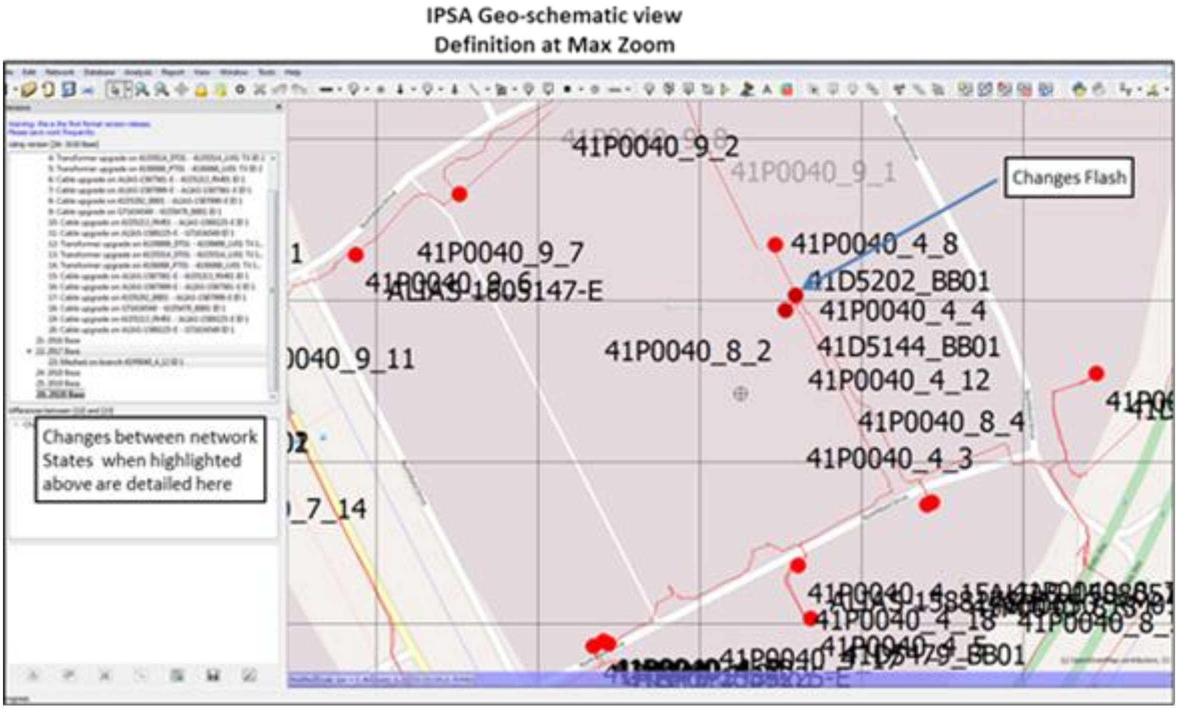
Figure 31: SIM On-board Results Browser



Source: FALCON Project SIM Results Browser

Network evolutions can be viewed directly using the captive IPSA capabilities when using the SIM. Such network representations are presented as a geoschematic representation of the network on a street map background. This capability provides an overview of the network, and when comparing network states it is possible for the user to select equipment changes in a side window and this causes that asset to flash clearly on the main diagram thereby drawing the Users attention to the assets affected if they are contained within the current window.

Figure 32: IPSA Geoschematic View of a Network Correspoding to a Given State



Source: FALCON Project, IPSA Viewing Tools

The Authorised Network Model provided data but did not provide the information required to create a schematic view of the network. For planning it would be useful to have the ability to see a clearer view of connectivity such as that provided by a traditional schematic view. This would be especially useful for showing where meshes had been created as the location of normal open points is not displayed, but requires interrogation of underlying data at the right location. An alternative might be to create one-line diagrams algorithmically from the connectivity data already within the database rather than creating another schematic view which needs to be routinely updated.

6.2.2 Analysis of Specific Runs

The Runs that are described in more detail below are given in table 7 earlier in this document.

6.2.2.1 Comparison of Results for Newport Pagnell Primary Substation

As with all such single primary network analysis areas, this analysis concerns the network area around this primary (including secondary substations) and includes adjacent feeders that could be involved with mesh or ALT activities.

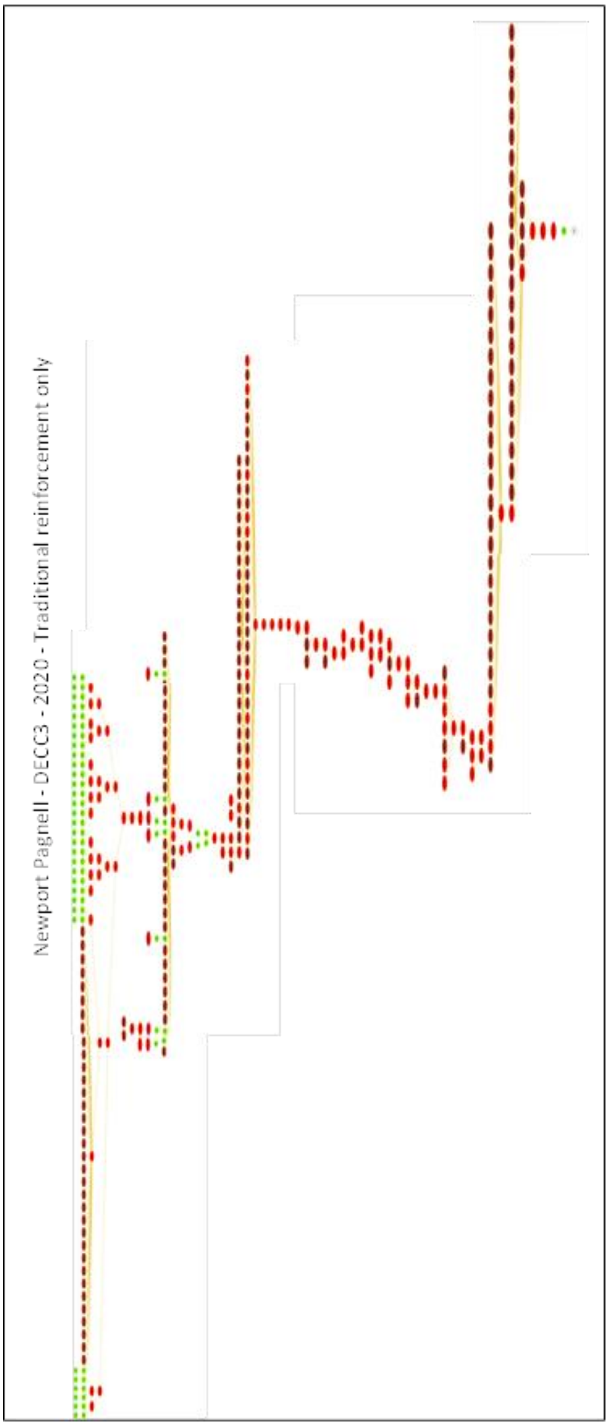
Two studies were carried out using the DECC3 demand scenario at Newport Pagnell:

- RUN A - DECC3 (32Results, 629 Network States Traditional reinforcement techniques only; and

- RUN B - DECC3 (16 Results, 356 Network States All Techniques.

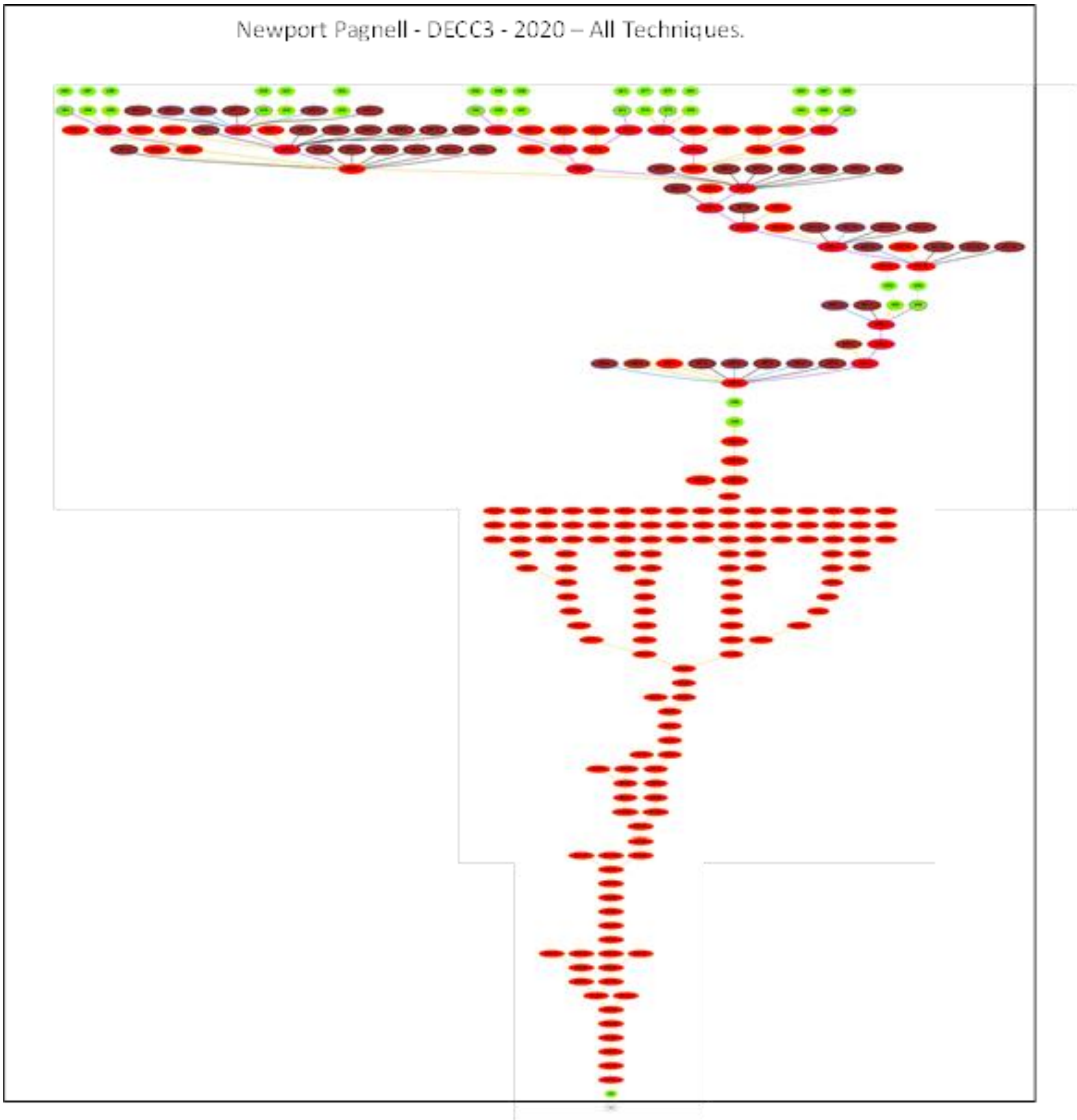
The SIM results trees for both studies are complex and difficult to view, however, an impression of the complexity of the result tree is gained by inspecting the following:

Figure 33: Full Result Tree Expansion for Newport Pagnell (Traditional Reinforcement Only)



Source: FALCON Project

Figure 34: Full Result Tree Expansion for Newport Pagnell (All Techniques)



Source: FALCON Project

In the first year, both studies identify the existing network as having 44 asset groups with at least one failure. The total number of failures can be very high because a failure counts as an asset with voltage or thermal limits exceeded for a half hour period. Each half hour period is considered a unique failure and these are counted separately according to the type of issue (thermal or voltage), the representative day type, and whether it occurs when analysing the network that is intact or under N-1 conditions. It is also important to note that the overload threshold on asset current ratings was set at 1% above their seasonal ratings both for normal feeding conditions and for N-1 conditions. Any value above 1.1% would therefore register as a failed asset. As noted elsewhere tuning of the

SIM management parameters needs to be assessed as this clearly yields many failures and resetting the thresholds to a business selected value would tune out those small transgressions so that fewer / higher load failure would be highlighted.

In a production version of the SIM, any failures caused by misrepresentations in the Authorised Network Model, or inaccuracies in the Energy Model would be eliminated by extensive validation. However, on the prototype version it is expected that there will be some failures reported initially due to imperfect data.

The approach taken in the SIM RUNs is to allow for the techniques used in the first year of analysis to be tailored. For example, they can be limited to traditional reinforcement only with a view that a few corrections are applied to resolve network issues after which the impact of load growth on a healthy network can be seen more clearly. While this feature is aimed at the Strategic Planner, the selection of permissible techniques will also affect the results returned by the 11kV Planner for shorter term Runs. In the Runs performed some included techniques 73, transfer load to adjacent feeder and 74, create new feeder in the initial year, which provides more options for the simulation and can create a more complex branching structure. Similarly the A* search algorithm was being refined during the RUNs and later versions could be seen to expand branches more efficiently. The RUN deploying all techniques produces 16 successful results after five years for a total cost of between £2.9 and £3.02 million in expenditure over the five years. Of the new techniques, patches were created for Battery installation, DAR and Mesh, but the branches of the simulation that involved batteries were not expanded. i.e. these branches were not selected by the A* search as they were expensive, so no use of batteries was included in the results. (Batteries were included in the later runs that extended to 2050).

The search was not continued until all possible options were exhausted, but rather the Run was paused when sufficient results had been achieved to get an overview of the likely pattern of reinforcements required. Had the search been Run for a longer time then more results would have been produced, but the operation of the A* search is such that the overall value for money of the results produced is likely to get worse over time.

Runs that were limited to traditional reinforcement produced over 30 results at a total cost ranging from £3.22 to £3.27 million. The difference in total cost of the two Runs indicates that utilising the new techniques could save in the region of £200,000, approximately six percent, in the first five years. The savings achieved are likely to vary according to the amount of investment required, reflecting the time period under consideration and the load scenario.

The visualisation of the results do not highlight whether the same sections of the cable network are worked on in consecutive years. Repeated interventions on the same network would not be desirable from customer relations prospective. This can be determined from the detailed results in the database and has been added to the set of standard reports used for analysing the Runs to 2050. This would be more apparent if the step by step network display was easier to interpret. A more detailed step-by-step progress display perhaps in a traditional IPSA schematic view would be an option, but other alternatives, such as an investment heat map showing the areas of network with repeated investment in a single image may also be useful. To reduce repeated investment on the same area of network it would be possible to include an additional cost within an experiment which could be applied after Runs were completed or as part of the cost metric used to direct the A star search.

Comparing a DECC2 All Techniques study at Newport Pagnell, Run C, with the all Techniques DECC3 study (B) above shows a very similar pattern of results. This again successfully deploys the DAR Technique and the study produces six positive results at between £2.88 and £2.99 million total cost for the five years. There is a relatively small cost difference of approx. £20k in the minimum cost solutions between these two different DECC scenarios.

6.2.2.2 Comparison of Results for Fox Milne Primary Substation

Two studies were carried out using the DECC4 Demand Scenario at Fox Milne. These were:

- RUN D - DECC4 (81 Results, 634 Network States)Traditional reinforcement techniques only; and
- RUN E - DECC4 9112 Results, 287 Network States) All Techniques. See below.

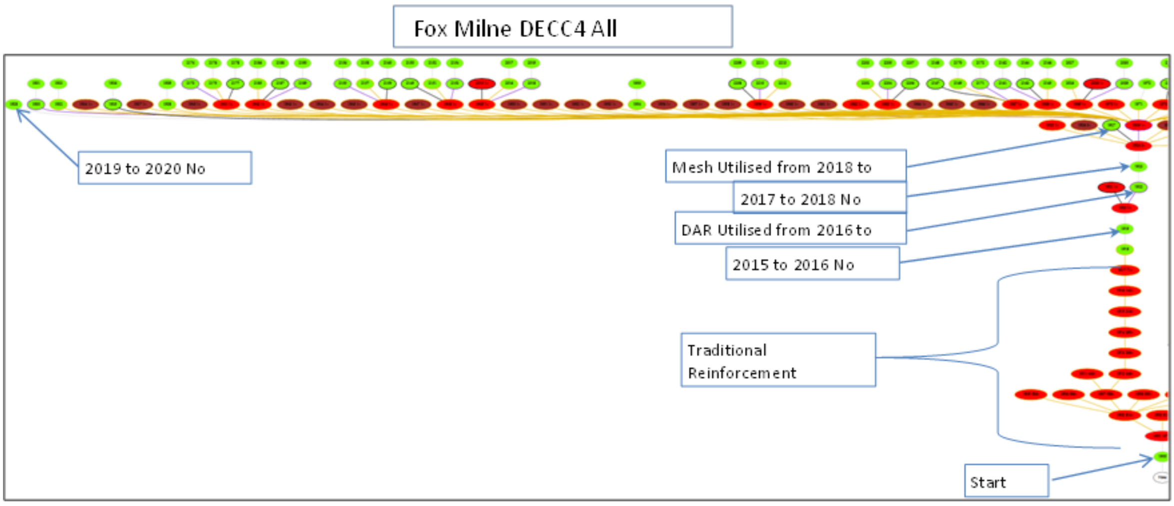
Both studies identify nine failed assets at the beginning of the process in 2015 and proceed to resolve them with traditional reinforcement in year one.

The results for RUN D include over 600 network states and this yields a very expansive flat tree diagram. It is not possible to display this within the report. In the first year, the nine problems are resolved by replacing assets for those of a larger capacity. In subsequent years the SIM continues to try combinations of transferring load and replacing assets resulting in 81 successful solutions, the cheapest of which has a cost of £264k.

An extract from the result tree for RUN E shows that the study reaches one of its successful results by utilising DAR and then the Mesh Technique for a total cost of £256k over the 5 years. Whilst other successful results are achieved for a few hundred pounds more by consecutive application of DAR.

RUN F is comparing the DECC1 study carried out for the same primary substation and shows similar results to E. above, with combinations of DAR and Mesh techniques producing positive results.

Figure 35: SIM RUN for Fox Milne Primary, All Techniques



Source: FALCON Project

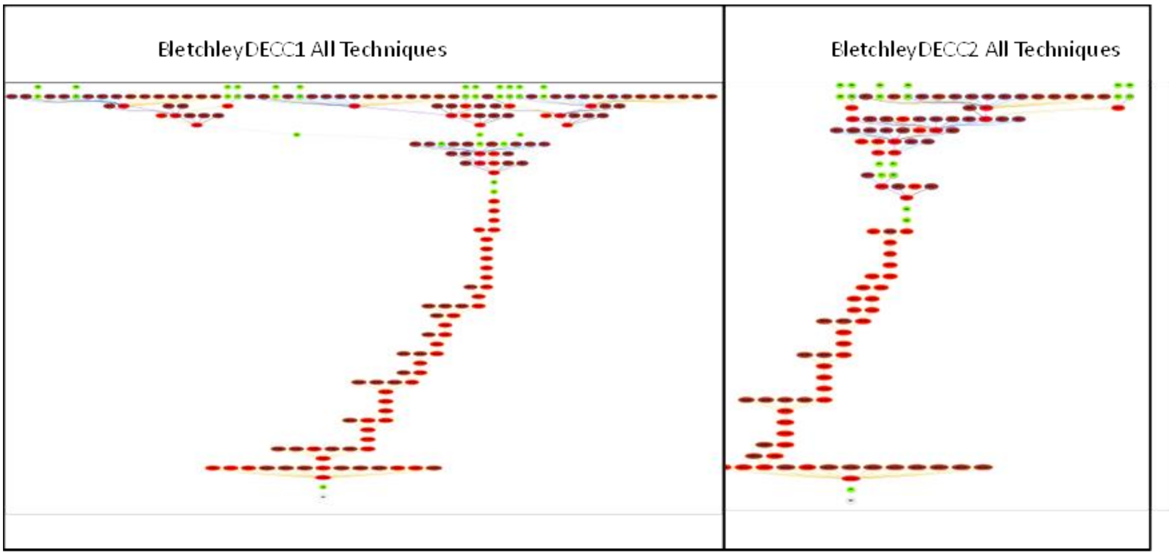
6.2.2.3 Comparison of Results for Bletchley Primary Substation

Two studies were carried out at Bletchley these were:

- RUN G - DECC1 All Techniques Traditional reinforcement techniques only; and
- RUN H - DECC2 All Techniques with techniques 73 & 74 enabled in 2015.

Both of these DECC load scenarios reveal 30 failures in 2015, however only 3 of the failures occur for an intact network while a further 27 occur during N-1 conditions. Both result trees follow a similar pattern where the 2015 failures are first solved with the application of traditional reinforcement. From 2016 onwards, DAR plays a large part in providing the solution. As expected there are more steps required to come to a satisfactory conclusion in 2020 for the more onerous DECC1 scenario.

Figure 36: SIM RUNS - Bletchley Primary, All Techniques - Different Demand Scenarios



Source: FALCON Project

6.2.3 Conclusions from Small Area Studies

The general conclusions are as follows:

1. The SIM is capable of branching multi-year simulations that use power flow analysis to identify network issues and programmatically created technique patches to resolve them;
2. The operation of the A*r search algorithm is robust and operates correctly so that results with the best value for money as determined by the cost metric are produced early in the simulation process;
3. Using smart techniques compared to traditional reinforcement alone will reduce the cost of operating distribution network under all load scenarios;
4. Thermal issues under N-1 conditions are the most common network issue. No voltage or fault level issues were found in the five year period analysed;
5. The investment required under different scenarios matches the expectations with the DECC4 scenario, reflecting low uptake of EVs and heat pumps leading to fewer network issues and lower levels of investment. Conversely the DECC3 scenario with the highest levels of uptake of EVs and heat pumps results in higher numbers of network issues and levels of investment;
6. Networks differ in the degree of investment required in the initial and following years. Secklow Gate primary was seen to have greater capacity such that no issues were present in 2015. Under the most onerous load scenario only one transformer became overloaded. Newport Pagnell on the other hand appeared to have exceeded capacity in 2015 with a large number of initial network issues, and further issues developing each year.

On the basis of the outputs from these SIM Runs it is also possible to draw a number of conclusions to verify how the 11kV Planner may interact with the SIM. This will inform both the SIM system development process as well as providing detail on the network. The usability conclusions are as follows:

7. These preliminary studies show that for a five-year study at a small number of Primary substations out to 2020 that around 24 results are obtained after a processing elapsed time of some 16 hours. It is important to note that the study/experiment may continue to run for much longer to exhaust all possible results in the search space. While currently long, the elapsed time taken to run a study should not be an issue for the 11kV Planner as once the study parameters are set he/she can leave the SIM to carry out the process by itself. Further performance optimisation is also foreseen as the options for improving processing times have not been fully explored, but rather the development effort has been directed mainly at functional correctness of the system. and improvement in the elapsed time for a Run may also be achieved by ensuring that settings and thresholds are set to appropriate levels, further tuning of

the A * search algorithm, using a custom order in which techniques are applied, tuning of the cost model values etc.

8. The SIM automatically Runs consecutive power flow studies based on parameters and thresholds that can bet set to suit business standards or set to include some or all of the new techniques. Careful attention to the setting of thresholds and parameters is necessary in order to maximise the usefulness of these outputs.
9. The IPSA representation of the results in a geo-schematic view might be improved to provide greater detail of the changes and connectivity, or alternatively, a link is required to a traditional schematic IPSA view where the network changes can be explored in greater detail.
10. In conclusion, the 11kV planners advised that for further development of the SIM it is essential that there is more involvement of *User Group* members, and that versions of the basic IPSA tool are made available to aid familiarisation with this key SIM component.

6.2.3.1 Relationship to Current Working Practices

11kV Planners in WPD mainly use DINIS currently to carry out power system analysis. Studies are run on an ad-hoc basis to satisfy new load connection enquiries. It is during this process that any problems with the existing network are revealed.

11kV Planners are unlikely to find time to carry out detailed analysis to aid short or medium term planning of the 11kV network in their area. However a fully functional SIM would allow the planner, with minimum input, to obtain a comprehensive view of the medium projected load growth for different DECC scenarios. This information would allow the planner to better deal with new connection enquiries and provide a higher level of confidence in the robustness of the network under different projected scenarios. It could also drive the production of a district 11kV Load Related Reinforcement Plan and provide evidence to help support submissions to Ofgem.

6.2.4 Validating Load Scenarios

Based on the Runs it is possible to make a number of speculative predictions for the Primary network areas that were analysed. These predictions include the likely range of load growth, the assets most likely to experience network issues, the time when these issues occur etc. These predictions can perhaps be verified in the future to confirm the results expected from the SIM performing modelling of the various possible outcomes. This would extend the comparison of monitored values to estimates that took place to validate the Energy Model to a longer term comparison which effectively validates the demand scenarios and would determine which scenario is most representative of Milton Keynes overall. To verify these predictions would need a view on Load growth (or decline, measured at each nodal point on the network) over the timeframe of the experiment and comparison of this to the modelled Demand scenarios. It is possible that detailed data may be available going forward as LVM equipment and the FALCON Communications Network needed to return the data are continuing to operate for the foreseeable future, but in any case the situation as it unfolds at these locations can be followed and used to compare with the predictions of the SIM made in this investigative phase.

6.3 SIM RUN Analysis

A series of SIM Runs were conducted to extract immediate learning from the SIM outputs, to exercise the SIM and gain Expert User familiarity with using it as an analysis tool.

Much of the analysis gives similar results, so for brevity not all results are included here but are given within the Appendix. Some summary results are presented here to illustrate the following general observations.

- Under all conditions most of the expenditure is seen in 2015 as apparent network issues are resolved. Secklow Gate is issue free in 2015 but Newport Pagnell has many issues to be resolved before the longer simulation can continue;
- Winter Peak and Winter Weekdays are still the day type when most issues arise, Spring Weekdays are the second most likely day for issues to occur;
- Thermal issues dominate the types of issue seen and these are far more prevalent for N-1 conditions as would be expected;
- Voltage issues were so infrequent initially that the voltage limits were tightened to generate more voltage issues to test the system. When voltage issues occurred these were all relating to low voltage rather than high voltage;
- No fault level issues were observed;
- Traditional reinforcement , especially cable/line upgrade accounts for the majority of interventions and costs;
- CMLs generally decline over time due to the adoption of smart techniques which reduce these;
- Cable utilisation generally increases over time;
- DAR was selected most often from the smart techniques followed by meshed networks. The other techniques (energy storage, DSM, DG and ALT) had very few useful installations and tended to be applied once other options were exhausted.

6.3.1 2020 Scenario Investigation – All Runs Combined

The combined Runs give a composite picture across all the load scenarios.

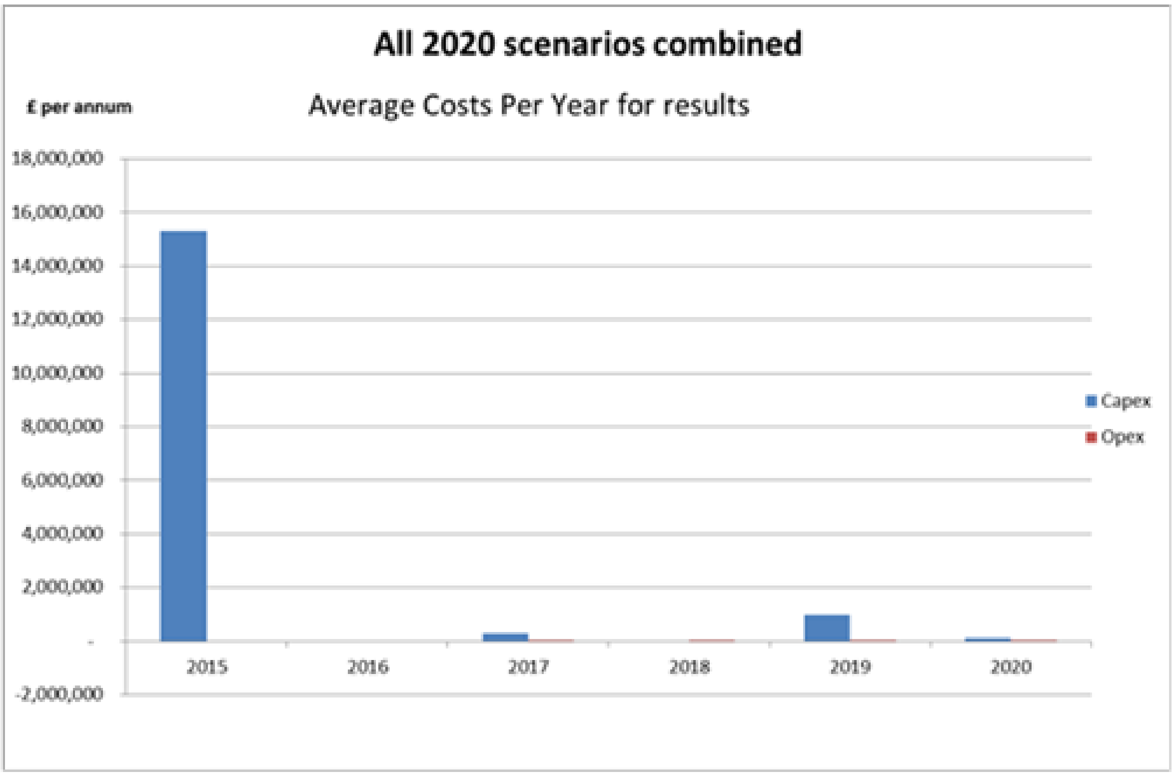
Host	EXP ID	Primary	Year	DECC	techniques	results	NS
sim2	4	Fox Milne	2020	DECC2	Smart & Traditional	67	206
sim2	6	Newport Pagnell	2020	DECC2	Smart & Traditional	24	481
sim2	17	Childs Way	2020	DECC2	Smart & Traditional	81	
sim1	4	Fox Milne	2020	DECC1	Smart & Traditional	75	213
sim1	6	Newport Pagnell	2020	DECC1	Smart & Traditional	12	399
sim1	8	Bletchley	2020	DECC1	Smart & Traditional	12	380
sim1	14	Marlborough St	2020	DECC1	Smart & Traditional	12	263

Host	EXP ID	Primary	Year	DECC	techniques	results	NS
sim3	16	Childs Way	2020	DECC3	Smart & Traditional	1366	3507
sim3	15	Bletchley	2020	DECC3	Smart & Traditional	52	749
sim3	6	Newport Pagnell	2020	DECC3	smart & Traditional	16	356
sim3	4	Fox Milne	2020	DECC3	smart & Traditional	109	304
sim4	4	Fox Milne	2020	DECC4	Smart & Traditional	112	287
sim4	10	Childs Way	2020	DECC4	smart & Traditional	91	1564
sim4	20	Bletchley	2020	DECC4	smart & Traditional	25	549
sim4	21	Marlborough St	2020	DECC4	smart & Traditional	51	415

6.3.1.1 Costs

As for the results that look at one scenario at a time, the majority of expenditure relates to ensuring the 2015 network is healthy before continuing the analysis, Additional expenditure in the following years fluctuates with the highest spend in 2019. OPEX is negligible compared to CAPEX.

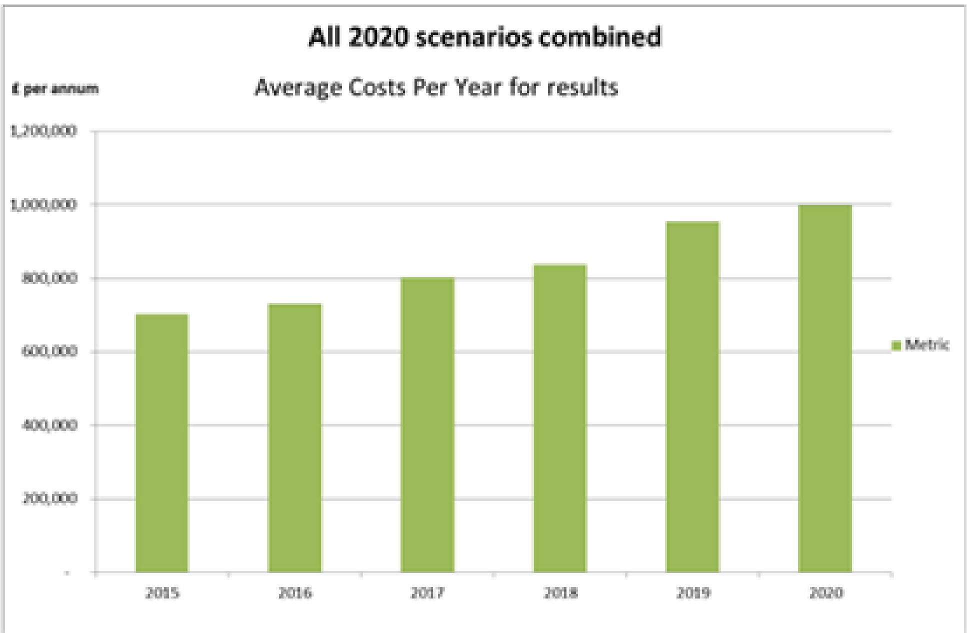
Figure 37: Scenarios to 2020 Opex and Capex Costs for Combined Results



Source: FALCON Project

While the CMLs are seen to decrease over time, the total metric costs increase due to the increasing financial values associated with CIs and CMLs and due to losses costs increasing as network utilisation increases.

Figure 38: Scenarios to 2020 - Average Metric Costs



Source: FALCON Project

Overall, traditional reinforcement makes up the vast majority of investment, with cable replacement being the most significant cost. These figures need to be revised following the discovery of a bug in how cable costs were being calculated.

All 2020 scenarios combined			
		Proportion of	
Technique Name	Number	Installations	CAPEX
DAR(Cable)	11	11%	1%
DAR (Transformer)	12	0%	0%
ALT	21	0%	0%
Mesh	31	3%	1%
Batteries	41	0%	0%
DSM	51	0%	0%
DG	61	0%	0%
Transformer replacement	71	10%	3%
Cable / line upgrade	72	73%	93%
Transfer load to adjacent feeder	73	2%	1%
New feeder	74	0%	2%

6.3.1.2 Timing of Issues

The majority of issues occur during Winter Peak and Winter Weekdays during the morning and evening peaks that are seen on the load profiles. There are some day types that do not experience network issues because remedial work is triggered following issues on the most onerous days before loads on these days become problematic. E.g. Autumn Saturday

Figure 39: 2020 RUNS Combined - Timing of Issues (First Year)

2020 all experiments combined																		
Year	2015				Operating condition					n-1								
Settlement period	Spring Weekday	Spring Saturday	Spring Sunday	Summer Weekday	Summer Saturday	Summer Sunday	High Summer Weekday	High Summer Saturday	High Summer Sunday	Autumn Weekday	Autumn Saturday	Autumn Sunday	Winter Weekday	Winter Saturday	Winter Sunday	Winter Peak	Summer Peak	PV Peak
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	102	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	113	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	113	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	113	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	113	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	113	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	102	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	102	0	0
9	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	6	0	0	6	0	0	6	0	0	6	0	0	6	0	0	6	6	6
11	12	0	0	12	0	0	12	0	0	9	0	0	9	0	0	9	12	11
12	58	0	0	18	0	0	53	0	0	32	0	0	30	0	0	30	44	14
13	104	0	0	60	0	0	83	0	0	65	0	0	66	0	0	67	82	20
14	150	0	0	123	0	0	127	0	0	126	0	0	138	0	0	168	124	70
15	236	0	0	154	0	0	184	0	0	143	0	0	257	0	0	289	177	63
16	269	0	3	218	1	0	280	2	0	241	0	0	410	28	27	453	290	80
17	271	0	4	210	1	0	271	3	0	216	0	1	438	97	96	505	269	101
18	218	2	4	184	3	0	255	3	0	168	0	1	530	142	142	616	255	110
19	189	0	3	161	1	0	218	3	0	134	0	0	490	140	120	576	197	108
20	131	0	3	158	1	0	182	3	0	131	0	0	382	95	94	518	180	107
21	110	0	1	115	1	0	158	1	0	129	0	0	214	49	49	463	157	106
22	68	0	0	111	0	0	117	1	0	99	0	0	166	4	4	368	111	96
23	66	0	0	111	0	0	111	0	0	99	0	0	164	3	3	269	111	96
24	64	0	0	111	1	0	110	0	0	98	0	0	133	3	3	214	111	95
25	64	0	0	112	1	0	108	0	0	98	0	0	131	3	1	203	110	95
26	64	0	0	118	1	0	108	0	0	98	0	0	131	1	1	177	110	95
27	65	0	0	110	0	0	108	0	0	98	0	0	131	1	1	166	108	95
28	66	0	0	108	0	0	108	0	0	99	0	0	131	0	0	165	107	96
29	66	0	0	110	0	0	108	0	0	100	0	0	160	1	0	188	108	96
30	67	0	0	110	0	0	108	0	0	131	0	0	166	1	0	204	108	96
31	68	0	0	111	0	0	111	0	0	131	0	0	184	3	0	366	108	104
32	75	0	1	113	0	0	112	0	0	135	0	0	361	38	23	476	110	104
33	97	0	1	119	1	0	115	0	0	142	0	1	448	49	44	555	113	105
34	120	0	3	143	1	0	120	1	0	289	0	3	440	50	44	557	115	105
35	125	0	3	143	1	0	143	1	0	298	0	3	414	49	44	497	120	106
36	115	0	1	119	1	0	120	1	0	198	0	1	303	4	0	381	118	105
37	124	0	3	108	1	0	116	1	0	130	0	1	199	3	0	232	106	99
38	53	0	3	39	1	0	43	1	0	62	0	1	63	1	0	94	39	34
39	25	0	1	25	1	0	27	1	0	23	0	0	24	0	0	55	25	23
40	25	0	1	25	1	0	27	1	0	18	0	0	18	0	0	49	27	23
41	16	0	0	15	0	0	16	0	0	9	0	0	9	0	0	9	16	15
42	9	0	0	9	0	0	8	0	0	6	0	0	7	0	0	8	8	9
43	6	0	0	6	0	0	6	0	0	6	0	0	6	0	0	6	6	6
44	6	0	0	6	0	0	6	0	0	6	0	0	6	0	0	6	6	6
45	5	0	0	4	0	0	4	0	0	3	0	0	2	0	0	3	4	3
46	1	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	1	1
47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Source: FALCON Project

Following the resolution of issues in 2015 there is a shift in the pattern of new issues. These are less likely to occur on Winter Peak days than previously and more likely to be spread more evenly between days.

Figure 40: 2020 RUNS Combined - Timing of Issues 2016 - 2027

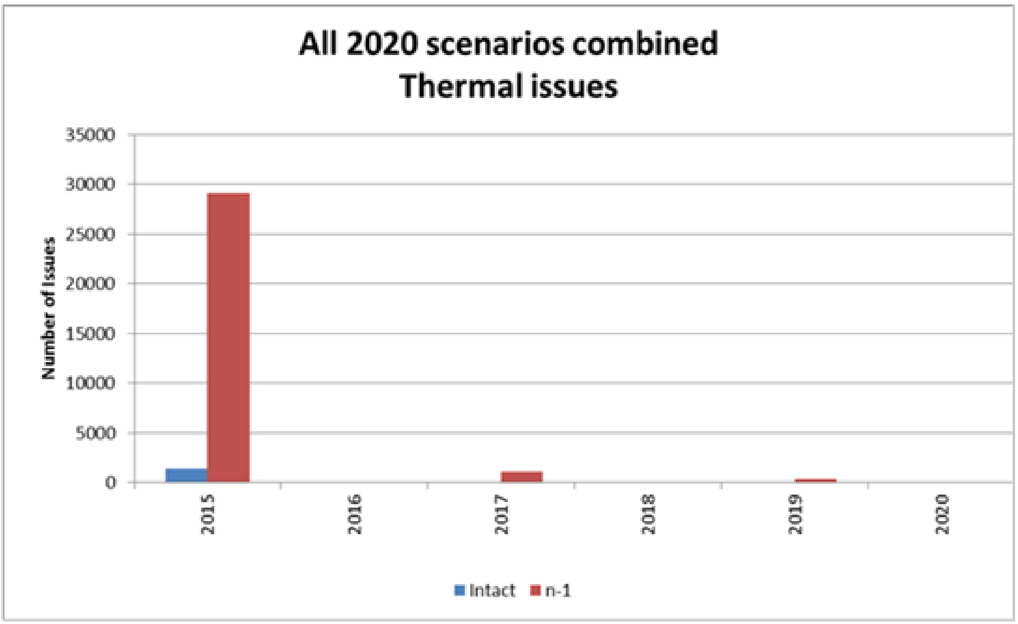
2020 all experiments combined																		
Year	2016 to 2027				Operating condition						n-1							
Settlement period	Spring Weekday	Spring Saturday	Spring Sunday	Summer Weekday	Summer Saturday	Summer Sunday	High Summer Weekday	High Summer Saturday	High Summer Sunday	Autumn Weekday	Autumn Saturday	Autumn Sunday	Winter Weekday	Winter Saturday	Winter Sunday	Winter Peak	Summer Peak	PV Peak
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	2	2	0	2	0	0	2	2	0	0	0	0	0	0	0	0	2	2
13	2	2	2	2	2	2	2	4	2	0	0	0	0	0	0	0	2	2
14	24.9	2	2	5.95	2	2	15.9	10	2	0	0	0	0	0	0	0	12	2
15	27.8	8	8	15.9	2	2	19.9	10	2	0	0	0	0	0	0	0	19.9	2
16	39.6	8	8	19.9	8	2	19.9	16	8	0	0	0	0	0	0	1	19.9	2
17	25.9	8	8	12	2	2	19.9	16	8	0	0	0	0	0	0	2	19.9	2
18	19.9	8	8	12	2	2	12	16	8	0	0	0	0	0	0	31	12	2
19	12	8	8	8	2	2	12	16	8	0	0	0	0	0	0	5	12	2
20	8	8	2	2	2	2	8	16	2	0	0	0	0	0	0	0	8	2
21	2	2	2	2	2	2	2	10	2	0	0	0	0	0	0	0	2	2
22	2	2	2	2	2	2	2	10	2	0	0	0	0	0	0	0	2	2
23	2	0	2	2	2	2	2	10	2	0	0	0	0	0	0	0	2	2
24	2	0	2	2	2	2	2	10	2	0	0	0	0	0	0	0	2	0
25	2	0	2	2	2	2	2	4	2	0	0	0	0	0	0	0	2	0
26	2	0	2	2	2	2	2	4	2	0	0	0	0	0	0	0	2	0
27	2	0	2	2	2	2	2	4	2	0	0	0	0	0	0	0	2	0
28	2	0	2	2	2	2	2	4	2	0	0	0	0	0	0	0	2	0
29	2	0	2	2	2	2	2	4	2	0	0	0	0	0	0	0	2	0
30	2	0	2	2	2	2	2	4	2	0	0	0	0	0	0	0	2	2
31	2	0	2	2	2	2	2	4	2	0	0	0	0	0	0	0	2	2
32	2	0	2	2	2	2	2	4	2	0	0	0	0	0	0	0	2	2
33	5.95	0	2	2	2	2	2	4	2	0	0	0	0	0	0	0	2	2
34	5.95	0	2	2	2	2	2	4	2	0	0	0	0	0	0	4	2	2
35	17.9	0	2	2	2	2	2	4	2	0	0	0	0	0	0	7	2	2
36	13.9	0	2	2	2	2	2	4	2	0	0	0	0	0	0	1	2	2
37	13.9	0	2	5.95	2	2	5.95	4	2	0	0	0	0	0	0	1	5.95	2
38	13.9	0	2	5.95	2	2	9.9	4	2	0	0	0	0	0	0	0	5.95	2
39	14.9	0	2	5.95	2	2	5.95	4	2	0	0	0	0	0	0	0	5.95	2
40	14.9	0	2	5.95	2	2	5.95	4	2	0	0	0	0	0	0	0	5.95	2
41	2	0	2	2	2	2	2	4	2	0	0	0	0	0	0	0	2	2
42	2	0	2	2	2	2	2	4	2	0	0	0	0	0	0	0	2	2
43	2	0	0	2	2	2	2	2	0	0	0	0	0	0	0	0	2	2
44	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Source: FALCON Project

6.3.1.3 Issues by type

Thermal Issues

Figure 41: Scenarios to 2020 Combined - Thermal Issues



Source: FALCON Project

Thermal Issues dominate this Run with the majority occurring in 2015 under N-1 conditions. Subsequent increases in load result in additional issues in 2017 and 2019. These issues are resolved in the year they occur and so overloads are not so large as to cause issues for the network under normal conditions.

Voltage Issues
Voltage issues were uncommon but did occur later in the later years of the longer simulations, typically after 2040.

Voltage issues were initially reported on the LV side of distribution transformers. The degree of low voltage suggests that issues may not be resolved by changing the transformer tap position and represents a genuine issue on the network. These low voltage issues were filtered out as the SIM harness was designed to focus on 11kV network issues and therefore was not able to determine the appropriate technique to apply to LV voltage issues. This did not result in underreporting of voltage issues in general as the voltage issues on the LV side of the transformer occurred at the same time as voltage issues on the 11kV network at the same sites. The decision was made to filter out voltage issues under N-1 conditions and focus on those that were seen during normal Running. Given the short term nature of faults on the 11kV network it is likely that other strategies such as transferring load beyond the initial feeders used for restoring supplies and providing generators to site to support voltage as required, would be more cost effective options than potentially very expensive investment.

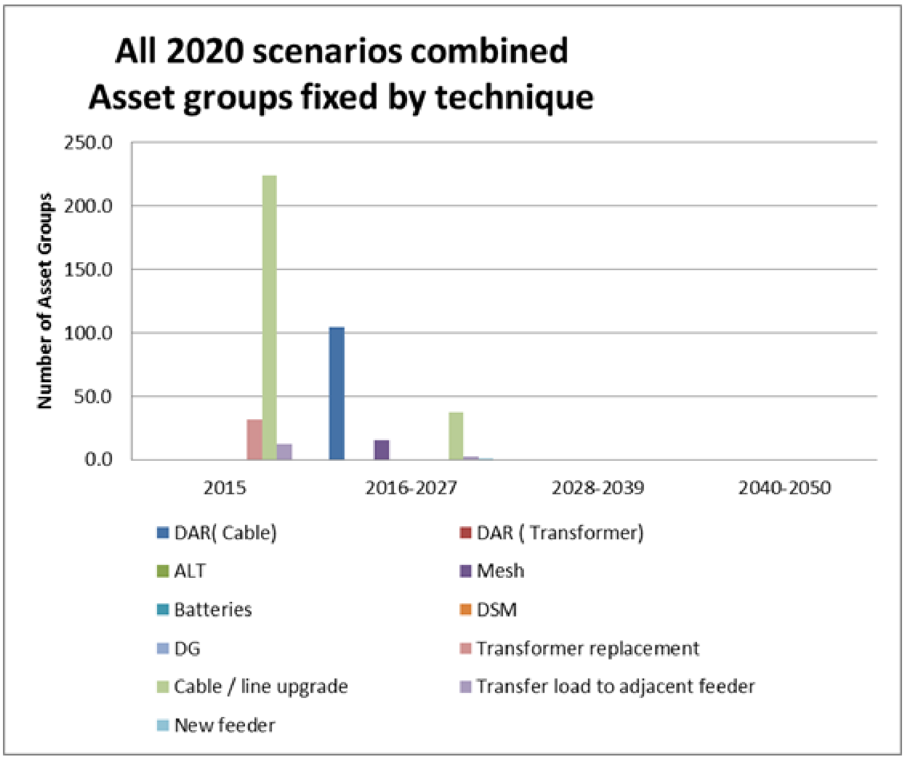
Voltage issues were seen on the intact network. The example below relates to Marlborough Street Primary. The SIM attempts to fix the voltage issues with traditional reinforcement, by creating a mesh and by applying batteries. Once the limit for the number of batteries applied to a feeder is reached the SIM finds no more useful options to resolve voltage issues.

6.3.1.4 Issues Resolved by Techniques

Techniques are applied to a selected asset group which has the most issues at the time of analysis. The impact of applying a technique can be to fix asset groups so that they have no remaining issues, or to reduce the number of issues.

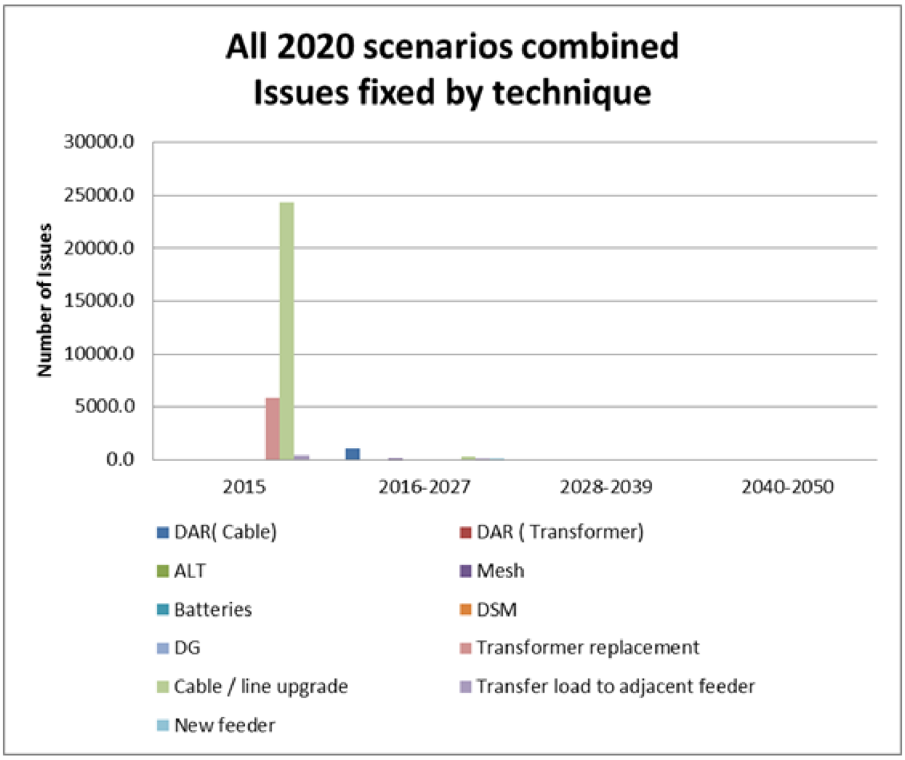
By either considering the asset groups fixed or the number of issues resolved, cable replacement is seen to be the most significant technique. DAR fixes a higher proportion of asset groups than it does actual issues. This suggests that the assets fixed by DAR have a lower number of issues per assets, which is to be expected. Assets with a high number of issues would be better suited to traditional reinforcement than a dynamic technique.

Figure 42: Combined Scenarios to 2020 - Asset Groups Fixed by Technique



Source: FALCON Project

Figure 43: Combined Scenarios to 2020 - Issues Fixed by Technique



Source: FALCON Project

6.3.2 2050 RUNs Combined

This combined the results for 2050 Runs available at the time of analysis.
This gives a longer view than the combined results for 2020. The split of issues by type and issues resolved by technique is similar to the results for 2020.

Host	EXP ID	Primary	Year	DECC	Techniques	results	NS
sim2	1	Fox Milne	2050	DECC2	Smart & Traditional	57	653
sim2	3	Childs Way	2050	DECC2	Smart & Traditional	46	230
sim2	10	Secklow Gate	2050	DECC2	Smart & Traditional	432	
sim1	1	Fox Milne	2050	DECC1	Smart & Traditional	80	726
sim1	19	Secklow Gate	2050	DECC1	Smart & Traditional	273	563
sim3	12	Secklow Gate	2050	DECC3	Smart & Traditional	118	635
sim3	3	Childs Way	2050	DECC3	Smart & Traditional	252	832
sim3	1	Fox Milne	2050	DECC3	Smart & Traditional	52	1004
sim4	1	Fox Milne	2050	DECC4	Smart & Traditional	172	768
sim4	2	Bletchley	2050	DECC4	Smart & Traditional	172	592
sim4	3	Childs Way	2050	DECC4	Smart & Traditional	10	128
sim4	12	Secklow Gate	2050	DECC4	smart & Traditional	7	9

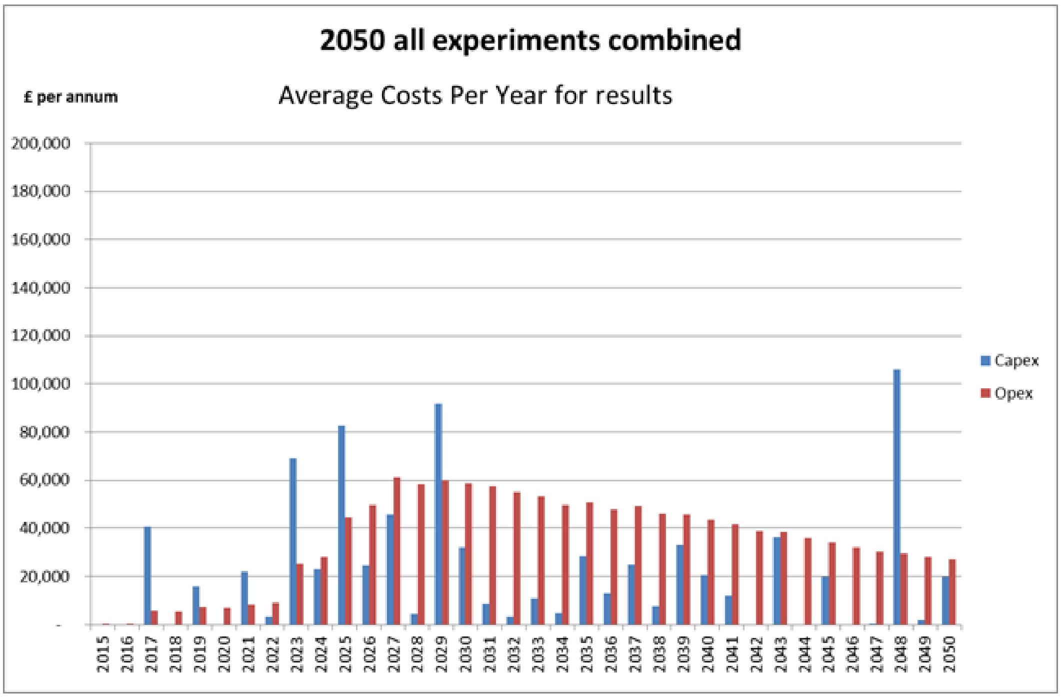
Host	EXP ID	Primary	Year	DECC	Techniques	results	NS
sim4	18	Marlborough St	2050	DECC4	smart & Traditional	25	512

This is not directly comparable to the 2020 Runs combined set which has a better balance between primaries. The 2050 set does not include Newport Pagnell and has only one Run for Marlborough Street and Bletchley.

6.3.2.1 Costs

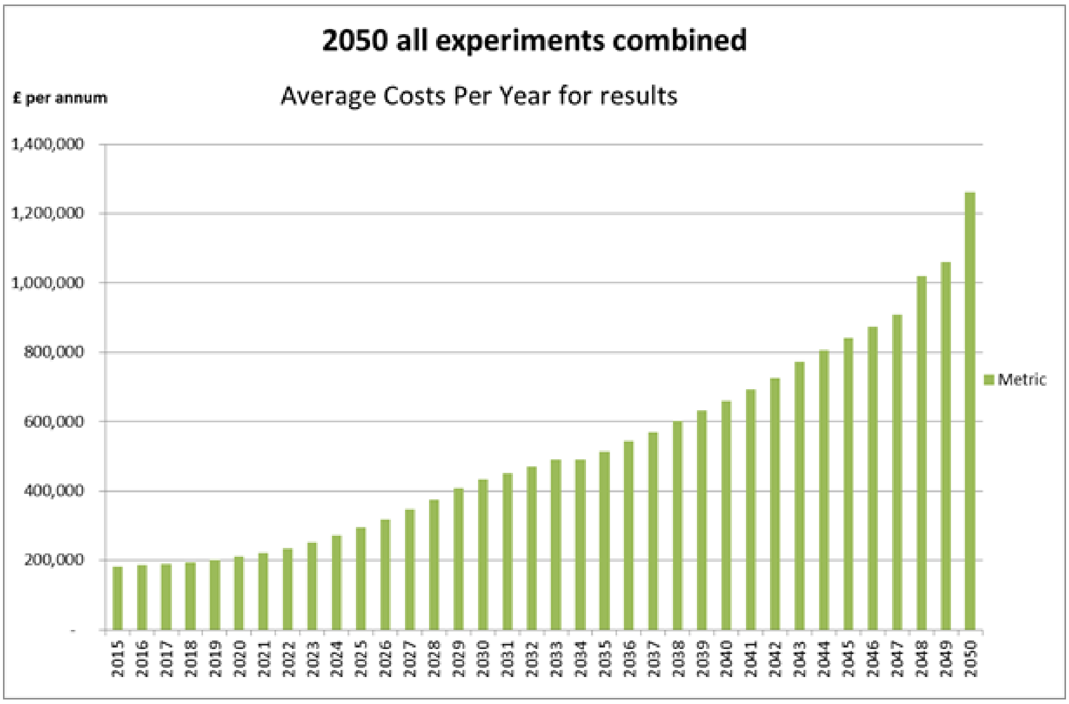
2015 costs have been removed for clarity – this is a combination of many Runs and so the total costs are not representative of what would be spent on the network, but this does show the lumpy nature of the CAPEX spend and the increase of OPEX costs. The costs in later years are reduced due to NPV adjustments being applied.

Figure 44: 2050 Experiments - All RUNs Combined - Average Costs per year



Source: FALCON Project

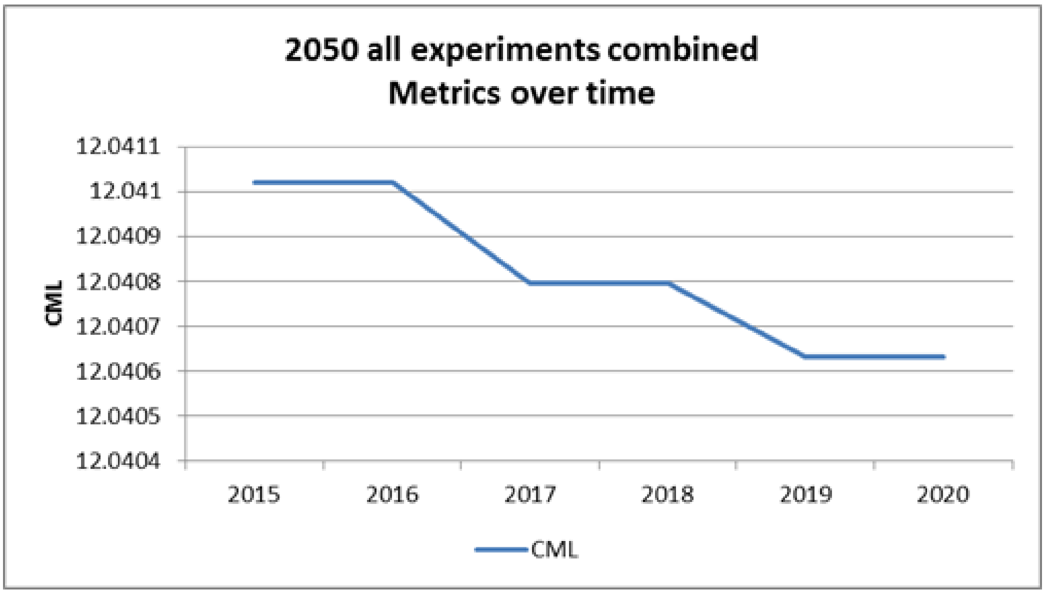
Figure 45: 2050 Experiments - All RUNs Combined - Average Metric Costs per Year



Source: FALCON Project

The Metric costs above account for the value of CMLs, CIs and Losses which increase due to increased loads and assumed increase in the value of CMLs and CIs

Figure 46: 2050 All Experiments - Combined Metrics over Time



Source: FALCON Project

Additional RUNs would be needed to remove any skew effect in the results based on the current low number of samples used.

Figure 47: 2050 Combined Experiments

2050 all experiments combined			
		Proportion of	
Technique Name	Number	Installation	Capex
DAR(Cable)	11	22%	5%
DAR (Transformer)	12	35%	11%
ALT	21	0%	0%
Mesh	31	4%	3%
Batteries	41	0%	0%
DSM	51	0%	0%
DG	61	0%	0%
Transformer replacement	71	16%	19%
Cable / line upgrade	72	21%	61%
Transfer load to adjacent feeder	73	1%	1%
New feeder	74	0%	1%

Source: FALCON Project

Traditional reinforcement remains the most significant technique to be applied with cable upgrade accounting for the majority of investment costs.

6.3.2.2 Timing of Issues

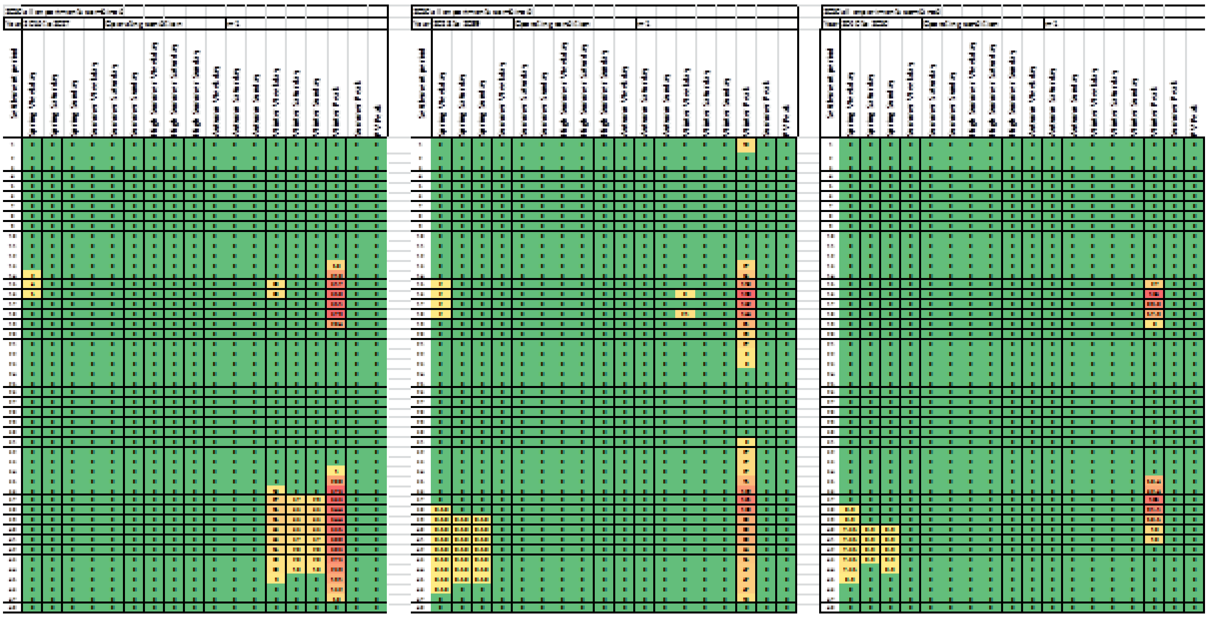
As for the 2020 combined RUN, Winter Peak remains the most onerous day type in 2015.

Figure 48: Timing of Issues - 2050 All RUNs (First Year)

2050 all experiments combined																		
Year	####				Operating condition						n-1							
Settlement period	Spring Weekday	Spring Saturday	Spring Sunday	Summer Weekday	Summer Saturday	Summer Sunday	High Summer Weekday	High Summer Saturday	High Summer Sunday	Autumn Weekday	Autumn Saturday	Autumn Sunday	Winter Weekday	Winter Saturday	Winter Sunday	Winter Peak	Summer Peak	PV Peak
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	14	0	0	0	0	0	2	0	0	18	0	0	36	0	0	54	0	0
15	20	0	0	4	0	0	14	0	0	36	0	0	56	0	0	74	14	0
16	22	0	0	14	0	0	19	0	0	51	0	0	64	2	2	83	20	0
17	22	0	0	14	0	0	17	0	0	14	0	0	65	8	8	86	17	0
18	17	0	0	12	0	0	16	0	0	12	0	0	73	12	12	95	16	0
19	16	0	0	12	0	0	14	0	0	0	0	0	70	12	10	92	12	0
20	12	0	0	12	0	0	12	0	0	0	0	0	62	8	8	72	12	0
21	12	0	0	6	0	0	12	0	0	0	0	0	30	4	4	68	12	0
22	2	0	0	0	0	0	10	0	0	0	0	0	12	0	0	61	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	12	0	0	52	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	30	0	0
25	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	12	0	0
26	0	0	0	12	0	0	0	0	0	0	0	0	0	0	0	12	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	0	0
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	0	0
29	0	0	0	0	0	0	0	0	0	0	0	0	12	0	0	12	0	0
30	0	0	0	0	0	0	0	0	0	0	0	0	12	0	0	12	0	0
31	0	0	0	0	0	0	0	0	0	0	0	0	12	0	0	57	0	0
32	12	0	0	0	0	0	0	0	0	0	0	0	26	3	2	70	0	0
33	14	0	0	0	0	0	0	0	0	0	0	0	34	4	4	92	0	0
34	16	0	0	2	0	0	0	0	0	19	0	0	34	4	4	92	0	0
35	7	0	0	2	0	0	2	0	0	14	0	0	34	4	4	55	0	0
36	4	0	0	0	0	0	0	0	0	5	0	0	14	0	0	42	0	0
37	5	0	0	0	0	0	0	0	0	0	0	0	6	0	0	24	0	0
38	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	0	0
39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	0	0
40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	0	0
41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Source: FALCON Project

Figure 42: Timing of Issues - 2050 All RUNs (2016 Onwards)



Source: FALCON Project

In subsequent years to 2015 Winter Peak remains the day most likely to experience issues but other days also experience issues such as Spring Weekday and Winter Weekday.

6.4 The FALCON Extended Strategic RUN Set

Following completion of the SIM development and testing phases, an initial set of investigative Runs and some investigatory work carried out by the FALCON team in conjunction with 11kV Planners, a series of SIM Experiment “RUNs” were planned. These Runs would use the SIM as an evaluation tool in order to explore network response to a number of trials area evolution scenarios and to gauge the engineering and commercial responses. Following analysis of these Runs by the project team, it is possible to draw a number of conclusions relating to network management and planning strategies.

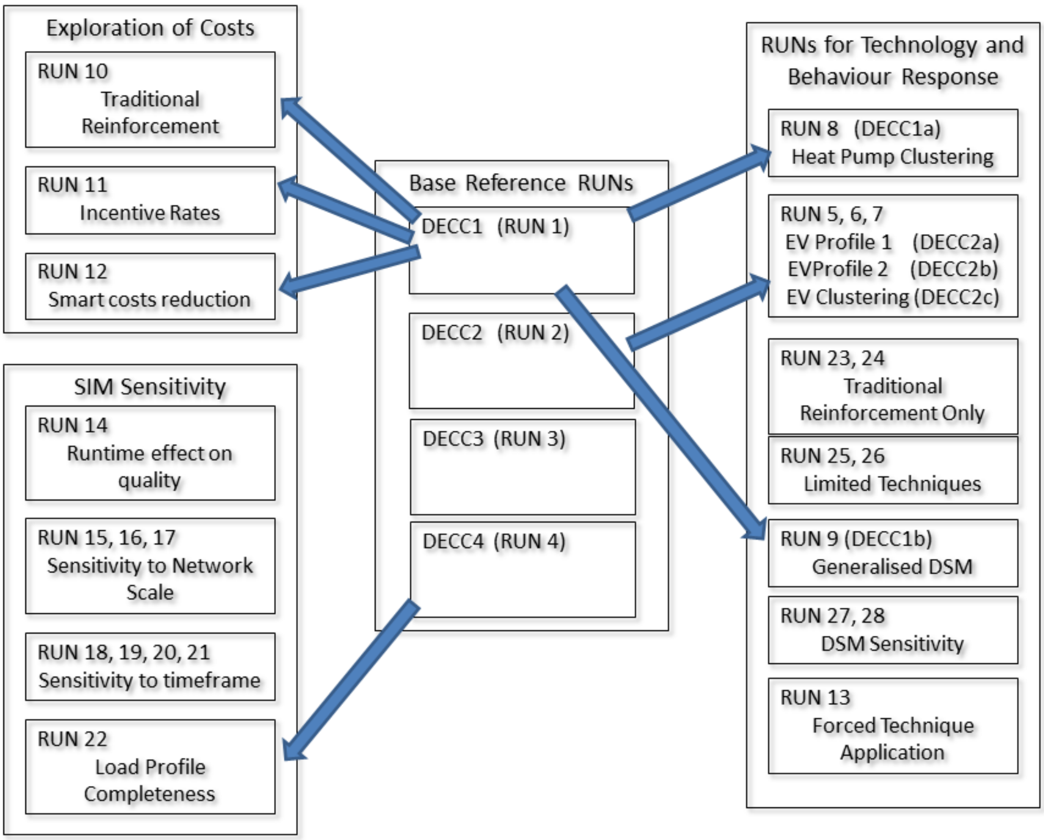
The overall Experiment set was defined to expand on the initial investigatory work and to explore a number of different operating scenarios, mainly at the strategic level, but also to probe the SIM’s own capabilities and limitations. Twenty eight Runs of the SIM were defined in the strategic investigation RUN set and these fall into a number of logically associated groupings which looking at different aspects of the network evolutionary modelling:

- Runs 1 – 4 Base Reference Runs against which a number of subsequent SIM Experiments (which adjust some of the assumptions and parameters) can be assessed. These four main Runs form the initial core objectives for the FALCON Project Report and have already been discussed in outline in sections above within this document. The Runs are each predicated on the use of one of the four main Department of Energy and Climate Change (DECC) demand scenarios numbered DECC1 – DECC4;

- Runs 5 – 7 Sensitivity testing against Electric Vehicle (EV) take-up (including different charge profiles and assessing also clustering effects across the network;
- Runs 8 – 12 Sensitivity testing across a number of areas including Heat pump take-up, DSM use, incentive costs, and smart solutions;
- Miscellaneous, Runs 13, 14 & 22 covering forced techniques, processing time VS quality and Load Estimation completeness;
- Runs 15 – 17 Scale sensitivity covering how well the system responds to modelling aggregated partial networks;
- Runs 18 – 21 Sensitivity to the planning timeframe;
- Runs 23 & 24, Traditional Reinforcement only, parts 1 & 2;
- Runs 25 & 26 modelling limited technique availability;
- RUNS 27 & 28 DSM Sensitivity, parts 1 & 2.

This overall RUN set is shown in Figure 49 below which also shows the Demand Scenarios invoked to support the RUNs. The diagram shows how the various RUNs are predicated on the core four reference model RUNs (DECC1 – 4) and in some cases utilise variants of these. Additional tests beyond the initial investigations conducted during FALCON and presented in this report may be drawn from this overall RUN plan to conduct further investigative work.

Figure 49: SIM Experiment RUN Set, Classified by Area



Source: FALCON Project

6.5 Sensitivity Analysis

By executing multiple Runs of the SIM with controlled differences between them in areas being probed for sensitivity of network response to the adjusted control parameters it will be possible to carry out sensitivity analysis in a number of areas. The sort of questions to be asked in this area include the impact of a change in:

- Clustering factors for electric vehicles (uneven distribution on the network);
- Clustering factors for heat pumps (uneven distribution on the network);
- EV charging profiles – smoother assumptions;
- Cost model – change to assumed costs of installation, weighting of non-cost components (CML, CI, Losses);
- Load Profile interpolation (as a pragmatic approach to not having complete Energy Model generated datasets);
- Simulation extent (accuracy response to duration of timeframe for the overall Runs);
- Processing cutoffs (when to stop – which metrics to use to measure the best time to end a processing RUN.

6.6 Comparison to Transform Model Results

One of the project objectives was to be able to determine the how the differences in output between SIM and Transform relate to the differences in inputs and processing methodology between these two network modelling systems. For example, is it possible to take a view on the impact of nodal model vs representative network approach and separate this from differences in:

- Techniques available;
- Cost assumptions;
- Load profile assumptions;
- Methodology to apply techniques;
- Expected levels of investment for each scenario.
- Unfortunately it is not a straightforward matter to try and compare the Transform Model and the SIM directly, not least because of the current SIM capabilities for modelling larger network areas.

6.6.1 Model Comparison

Given the differences between the models, the comparisons need to be quite general and the following areas of comparison are considered in the sections below:

- Load Profiles;
- Proposed Investment by solution type;
- Costs associated with solutions;
- Benefits of solutions;
- Losses;
- Customer interruptions;
- Investment Triggers (Voltage vs Thermal issues);
- Sensitivities.

6.6.2 Objectives

The SIM has a number of overlaps with the Transform model used for ED1 planning, but there are also a number of key differences. The most significant difference is the way in which the modelling tools determine the headroom on networks and apply solutions. For Transform, the network is modelled as a set of representative network types with standard default values for voltage and thermal headroom. The model determines the impact of load changes to reduce headroom and for solutions to release headroom. While these values have been derived from power flow analysis on networks, there is no actual power flow analysis within the Transform model itself. It was intended to compare outputs from the SIM to those from Transform to determine the similarities and differences and to consider whether the modelling within the SIM would provide a better basis for planning for the ED2 price control.

6.6.3 Differences between the SIM and Transform Models

- The modelling approach is not the only difference between Transform and the SIM. The load profiles, range of solutions, prioritisation methodology, cost modelling and other features of the models reduce the chances of ascribing a particular difference in the output to a particular difference in the inputs or processing methodologies. The table below is intended to clarify the key differences and similarities between the models.

Aspect	Transform Model	SIM
Voltage layers covered	All voltages	11kV only in present version
Network analysis mechanism	Networks categorised as representative network types.	Analysis of actual networks using a nodal model.
Network Extent	Can be large, covering a DNO region	Currently small network sub-areas around clusters of primary substations due to network complexity, need for accurate data covering the area and the sheer size of the remedial actions and state databases that need to be maintained.
Techniques modelled	Wide variety of techniques plus traditional reinforcement.	Traditional reinforcement plus 6 new 11kV Techniques.
Scenarios used	3 DECC scenarios plus 1	4 Preset scenarios plus variable features to set up new scenarios as required.
Investment strategies	Business as usual, Top down and incremental	This does not support Topdown vs. Incremental analysis directly. The technique costs assume a marginal of the costs of the enabling technologies. The additional one-off enabling technology investment would be calculated and added in manually. Business as usual vs. smart can be modelled by making techniques unavailable within the evaluation period.
Time series data used for modelling	Seasons / days/ 39 years, 3 days (Summer average , Winter peak , Winter average) 48 half hours per day.	38 years 18 season day types per year. (Weekday, Saturday, Sunday x Averages for Autumn , Winter, Spring, Summer, High summer Plus Winter peak, summer peak, summer minimum 48 half hours per day.
Aspects analysed	Thermal overload Voltage Fault Level	Thermal Voltage (Fault level analysis may be available to 11kV planners using the tool but may not form part of the automated analysis.)
Modelling process	Looks to anticipate the best solution using a merit order approach with additional considerations added in, e.g.	All technical solutions that resolve the constraint are initially considered. This approach creates many branching results which can multiply up to a large number of

Aspect	Transform Model	SIM
	ensuring that that the techniques will solve the constraint for a specified time period.	solutions quickly. To manage the impact on performance, an algorithm is used to expand branches in a preferential order which is likely to ensure the best solutions are calculated within the time limitations.
Network Headroom estimation	Overall percentage values for each network type	Calculated for each network with the network modelling tool
Technique headroom release	Overall percentage value for each technique	Calculated for each technique as applied to each network.
Load estimation	GL Noble Denton model. More detailed modelling for domestic customers but few I&C archetypes.	Energy Savings Trust model More complete I&C modelling with a number of domestic customer profiles derived from analysis.
Mapping of customers to network	Based on averages	Based on real customer-to-network mapping
Mapping of Low carbon technology uptake and efficiency changes for customers	Based on regionalising the national DECC scenarios	Determined by customer type and mapped through to distribution substations via customer – network connectivity
CML/CI and losses impacts	CML/CI and losses impacts are based on generic assumptions for each technique.	Network model derived benefits can be calculated for CML/CIs and Losses.
Disturbance Factor	Disturbance factor	Disturbance factor approach adopted from WS3 model. Relative values may differ.
Cost changes over time	Technologies mapped onto different future cost curves according	This is facilitated within the cost models. Any cost curve can be accommodated.
Cost NPV assumptions	A fixed discount rate is assumed.	This is facilitated within the cost models and can be tailored
Clustering	Degree of clustering can be varied within the model	Clustering would need to be altered within the energy model rather than the SIM
Tipping points	Assessed in the report	Could be assessed manually from the reports but is not part of the system functionality.
Modelling wider electricity sector	This is beyond the scope of the network model but is part of the overall model that includes the economic assessment	Not a feature of this model
Asset replacement	While reinforcement is expected to last for 40 years, new solutions are expected to go after 20 years and are removed from the model	Technique lifetime will be specified to trigger replacement capital or removal of solution and replanning of a network to ensure the optimal solution rather than a like-for-like

Aspect	Transform Model	SIM
	as is their benefit.	replacement.
Modelling of solutions and enablers	Separate modelling of enablers such advanced control systems and telecoms from implementation of solutions	Cost of solutions contains an element to cover telecoms and IT costs rather than having these as a separate item.

6.6.4 Scale of Operation

FALCON only covers Milton Keynes which accounts for only 1.5% of East Midlands customers.

Therefore scaling the investment plans for the 11kV network from Milton Keynes to DNO level for comparison with the East Midlands investment plan is likely to provide only a very general test that the results are in the right order.

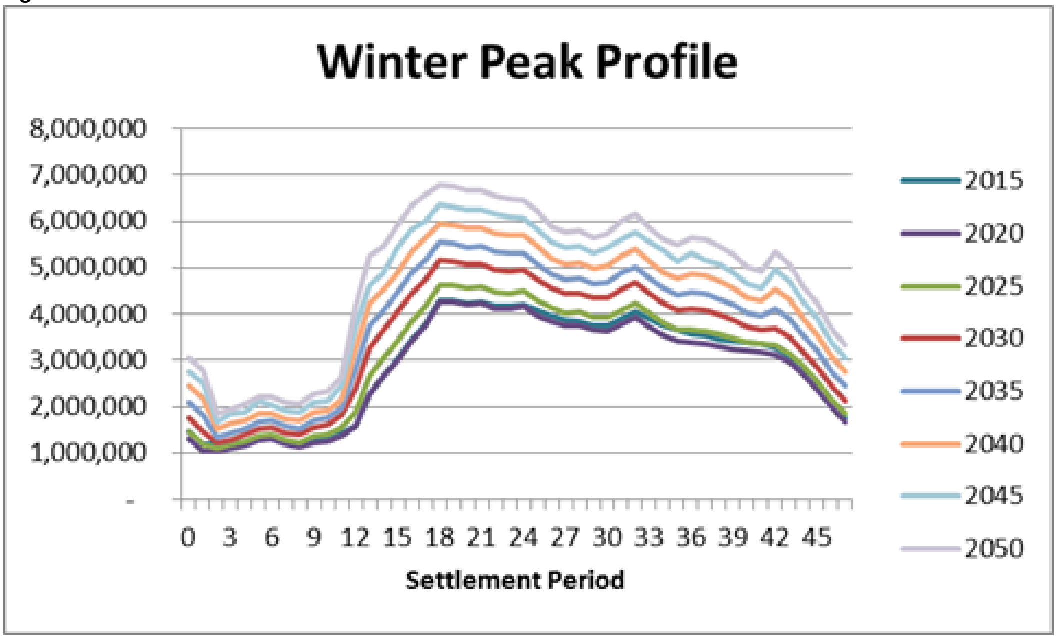
6.6.5 Load Profiles

The following Transform load profiles have been taken from the Transform Model "Results Input" sheet which is then used to populate other ED1 preparation spreadsheets.

This gives a combined view of the load profiles for the three modelled days, Winter Peak, Winter Average and Summer Average. The FALCON profiles for the nearest equivalent days for the nearest equivalent scenario (DECC1) have been added for comparison.

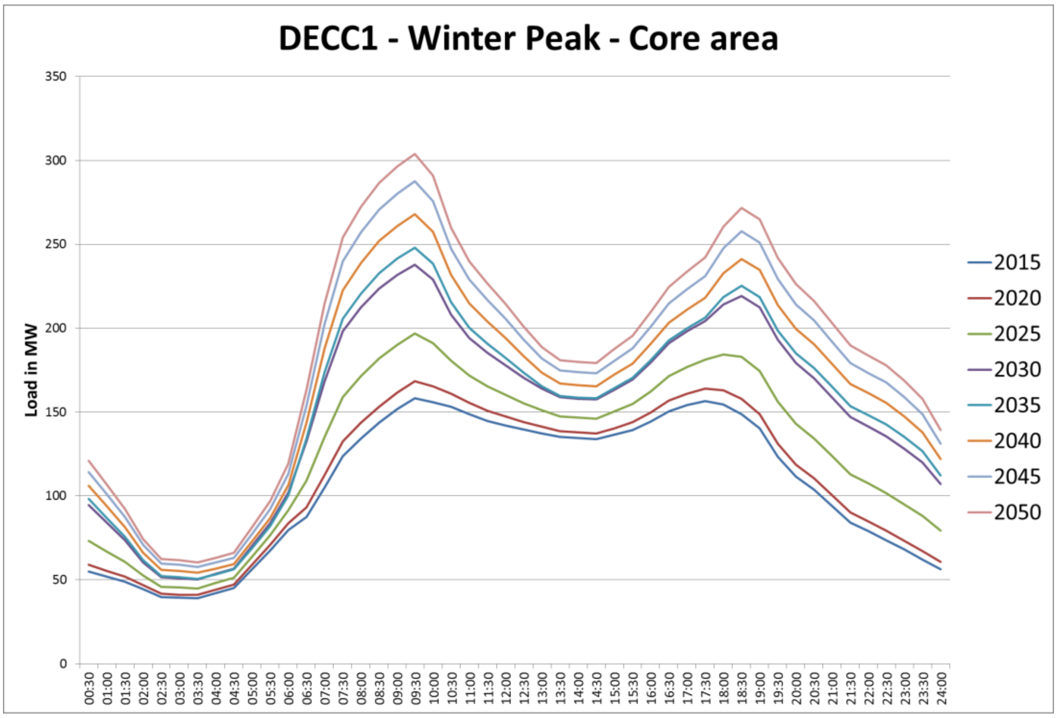
The fact that the combined profile shapes differ is not necessarily a concern because the profile shapes will reflect different assumed mixes of customers. Both profiles suggest a peak time of between 9 and 10am but FALCON assumed a faster increase in load in the earlier years.

Figure 50: Transform Load Profiles - Winter Peak



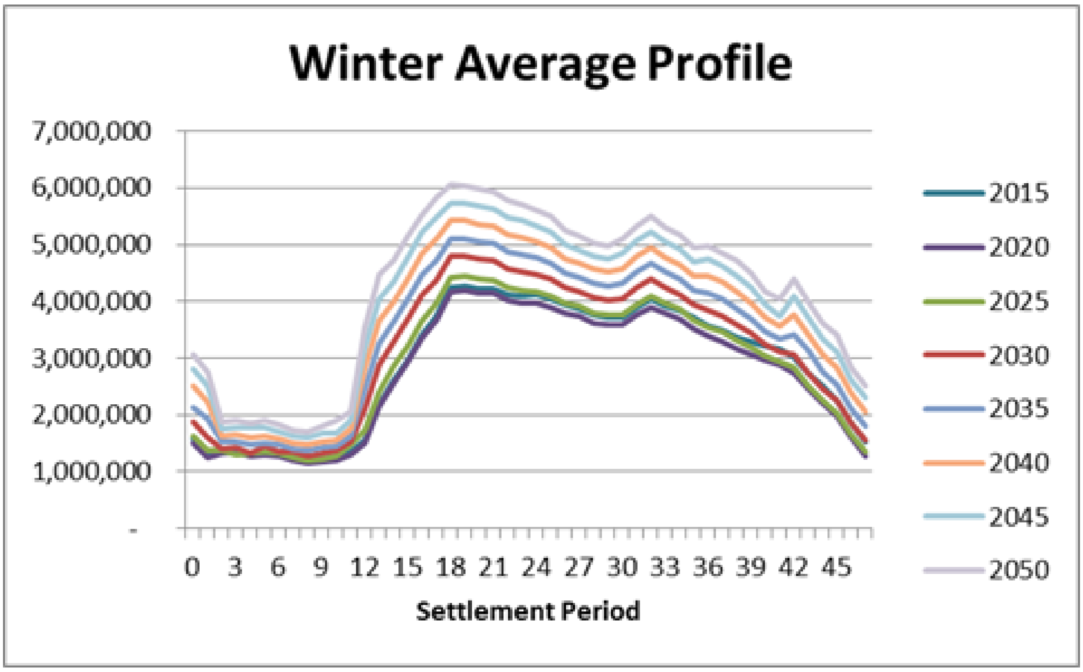
Source: Transform Model

Figure 51: DECC1 Winter Peak profile – Core FALCON area



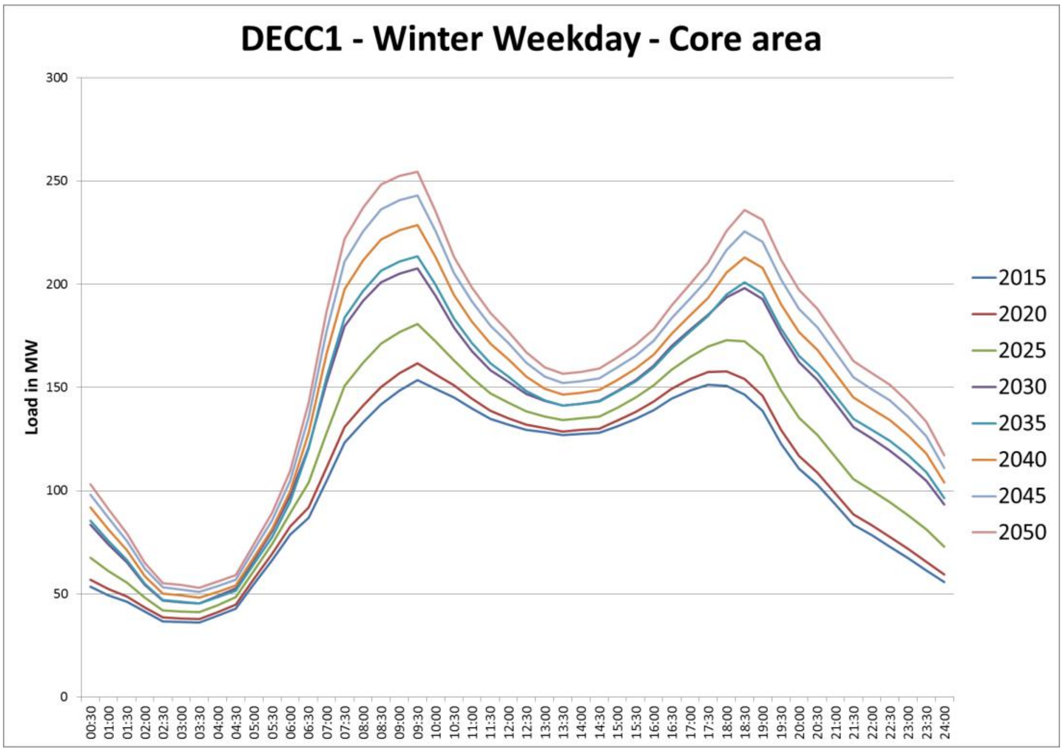
Source: FALCON load data

Figure 52: Load Profiles - Winter Average



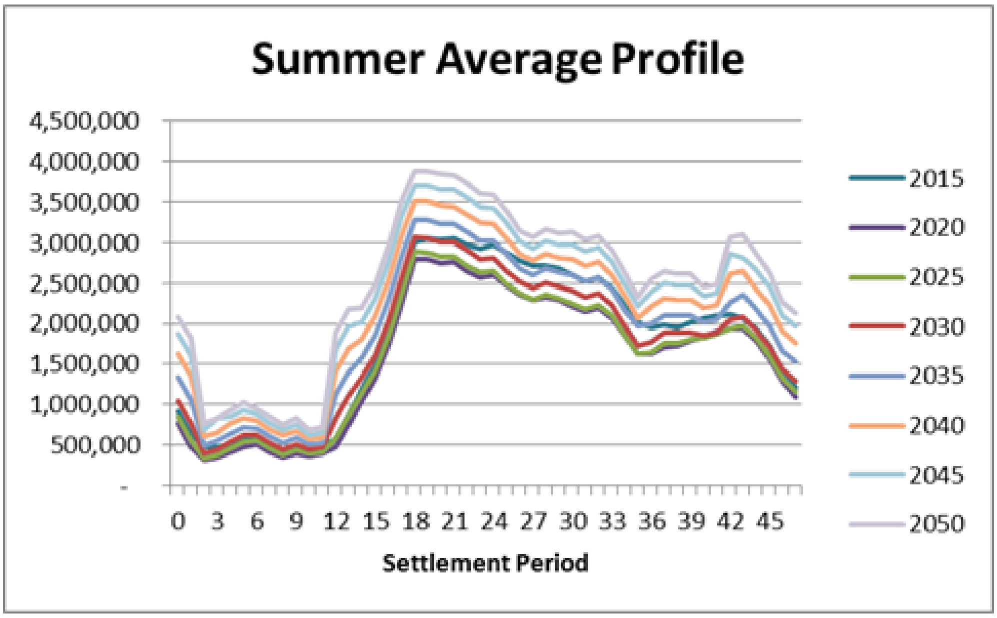
Source: Transform Model

Figure 53: FALCON Profiles DECC1 Winter Weekday Core area



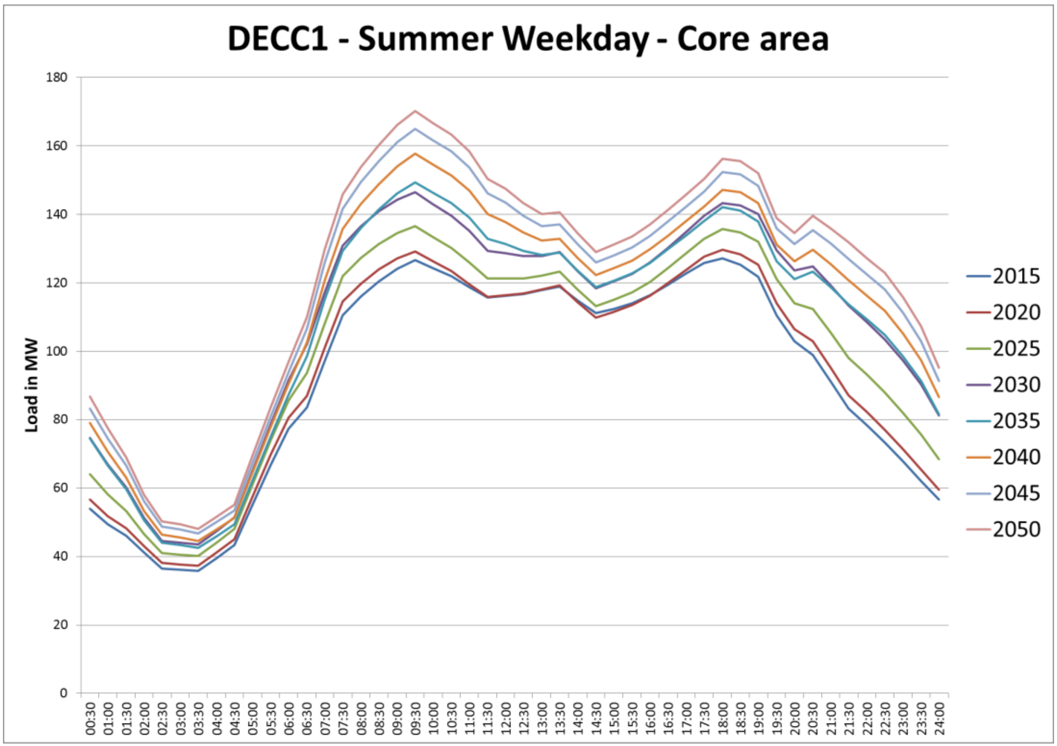
Source: FALCON Load Data

Figure 54: Transform Load Profiles – Summer Average



Source: Transform Model

Figure 55: DECC1 Summer Weekday – Core area



Source: FALCON Load Data

The Transform profiles suggest that load does not increase significantly between 2015 and 2020 and evening load actually reduces during this period. After 2025, load increases at a relatively stable rate. The load shape is largely consistent over time with the exception of the period between 8pm and 9pm. Winter Average and Winter Peak profiles, a peak develop a peak at this time in later years, and the existing peak for the Summer Average profile at this time becomes more pronounced. The time of the peak load is around 10am for all profiles.

The increase in peak load relative to the peak in 2015 is given in the table below.

Transform	Peak load as multiplier of 2015 peak load		
Year	Winter Peak	Winter Average	Summer Peak
2015	1	1	1
2020	0.99	0.98	0.91
2025	1.08	1.04	0.94
2030	1.20	1.12	1.00
2035	1.29	1.20	1.08
2040	1.38	1.27	1.15
2045	1.48	1.34	1.21
2050	1.58	1.42	1.27

The equivalent table for FALCON shows that FALCON's load assumptions are more onerous, expecting far higher load increases for Winter Peak. Summer Peak increases are of a similar order suggesting the difference relates to assumed electric heating requirements.

FALCON	Peak load as multiplier of 2015 peak load		
Year	Winter Peak	Winter Average	Summer Peak
2015	1	1	1
2020	1.06	1.05	1.02
2025	1.24	1.18	1.07
2030	1.50	1.35	1.15
2035	1.57	1.39	1.17
2040	1.69	1.49	1.24
2045	1.82	1.58	1.30
2050	1.92	1.66	1.34

6.6.6 Proposed Investment

The SIM and Transform both report on the expected spend on traditional reinforcement techniques and smart techniques.

The Transform model does not report the exact number of transformers replaced or length of linear assets installed. The model includes "feederisation factors" where the ratio of assets is used to determine how to share costs of upgrades. For example, if a ground mounted distribution transformer is replaced then the additional capacity will benefit all the LV feeders associated with it. Typically there would be five LV feeders for a ground mounted transformer so the costs associated with an LV upgrade might include 1/5th of the cost of replacing a transformer.

The Transform model was used to populate the sheet CV103 in the cost and volumes workbook for ED1. The table below represents the DNOs best view scenario which is reflective of Transform's DECC1 scenario "High abatement in low carbon heat".

Reproduced from CV103 – cost and volumes submission for ED1

Secondary network - Number of times implemented	2015	2016	2017	2018	2019	2020	2021	2022	2023	DPC R5	RIIO-ED1
Active Network Management - Dynamic	-	-	-	-	-	-	-	-	-	-	-

Secondary network - Number of times implemented	2015	2016	2017	2018	2019	2020	2021	2022	2023	DPC R5	RIIO-ED1
Network Reconfiguration											
Flexible AC Transmission Systems	-	-	-	-	-	-	-	-	-	-	-
D/GSR	-	-	-	-	-	-	-	-	-	-	-
Embedded DC Networks	-	-	-	-	-	-	-	-	-	-	-
Enhanced Automatic voltage Control (EAVC)	-	0.07	0.07	0.14	0.28	0.43	0.57	0.71	0.85	-	3.1
Fault Current Limiters	-	-	-	-	-	-	-	-	-	-	-
Generator Providing Network Support	-	2.27	2.27	4.54	9.08	13.63	18.17	22.71	27.25	-	99.9
Intelligent control devices (EVs)	-	-	-	-	-	-	-	-	-	-	-
New Types Of Circuit Infrastructure	-	-	-	-	-	-	-	-	-	-	-
Meshing (permanent)	-	7.23	7.23	14.46	28.92	43.38	57.85	72.31	86.77	-	318.2
Meshing (temporary)	-	0.58	0.58	1.17	2.34	3.51	4.68	5.84	7.01	-	25.7
Real-Time Thermal Rating	-	27.84	27.84	55.67	111.34	167.01	222.69	278.36	334.03	-	1,224.8
Switched Capacitors	-	0.48	0.48	0.95	1.90	2.85	3.81	4.76	5.71	-	20.9
Conventional reinforcement	-	56.12	56.12	112.24	224.49	336.73	448.97	561.22	673.46	-	2,469.4
Electrical Energy Storage	-	-	-	-	-	-	-	-	-	-	-
Smart Enabler	-	68.49	68.49	136.99	273.97	410.96	547.95	684.94	821.92	-	3,013.7

The table above shows the solution applied most often by transform is traditional reinforcement and that this is selected approximately twice as often as the next option, real-time thermal rating. After that the next most chosen option is permanent meshing with other selected options of generator support, temporary meshing and switched capacitors accounting for the remaining selection. A high volume of smart enablers are expected to be installed to support the smart techniques.

Generator support is a commercial option where generators actively export on to the network, rather than customers using their generation to support their own demand reduction. The techniques of D/GSR are equivalent to the commercial techniques of Demand Side Management / Generator use in FALCON. Similarly Active Network Management – Dynamic Network Reconfiguration is equivalent to the technique of Automatic Load Transfer within FALCON. Electrical Energy Storage is equivalent to battery storage within FALCON. These three techniques were not selected by Transform for ED1.

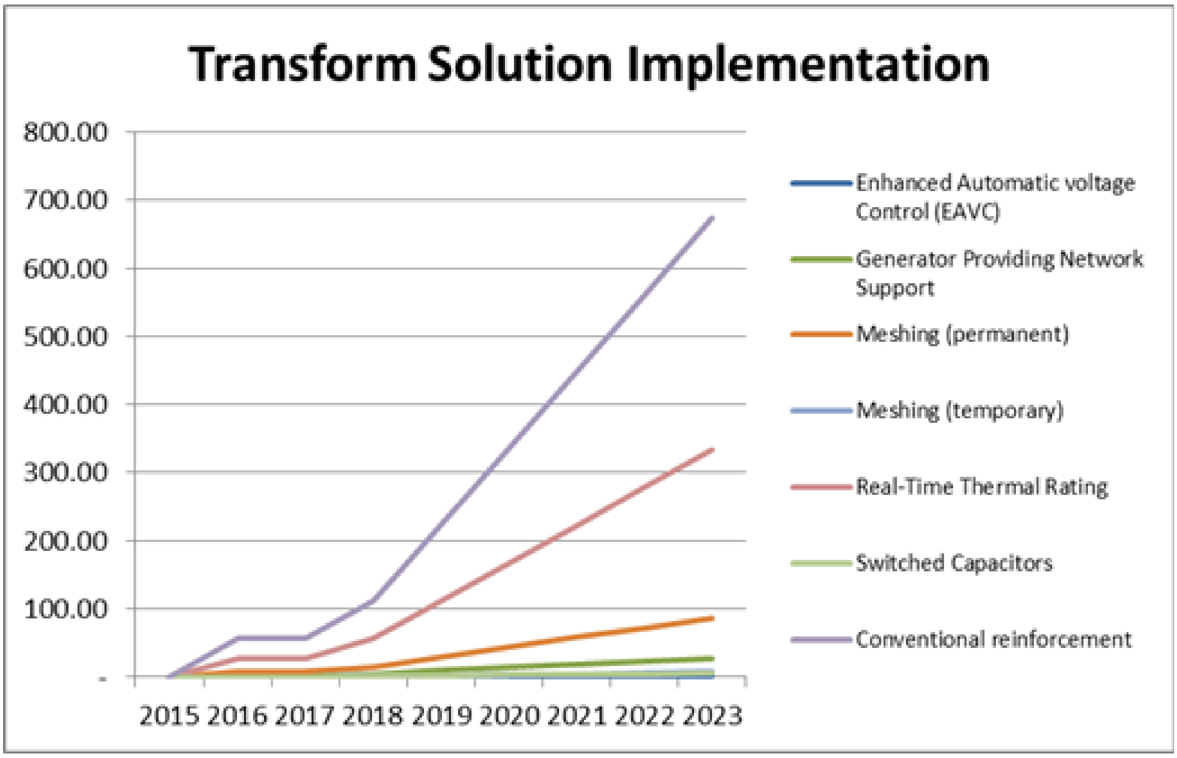
Solution	Percentage of Transform ED1 solutions reported *	Percentage of FALCON solutions to 2020
Conventional reinforcement	59%	87%
Real-Time Thermal Rating	29%	10%
Meshing (permanent)	8%	3%
Generator Providing Network Support	2%	0%
Meshing (temporary)	1%	0%
Switched Capacitors	1%	0%
Enhanced Automatic voltage Control (EAVC)	0%	0%
Active Network Management - Dynamic Network Reconfiguration	0%	0%
Flexible AC Transmission Systems	0%	0%
D/GSR	0%	0%
Embedded DC Networks	0%	0%
Fault Current Limiters	0%	0%
Intelligent control devices (EVs)	0%	0%
New Types Of Circuit Infrastructure	0%	0%
Electrical Energy Storage	0%	0%

*Excludes enablers.

FALCON is suggesting that traditional reinforcement will provide an even higher proportion of the solutions

No tabulated data is available to split the techniques that have been selected between Overhead or Underground network types.

Figure 56: Transform Model - Rate of Implementation



Source: <Insert Notes or Source>

The chart above shows that the rates of increase of installations are low between 2015 and 2017 when they start to accelerate at a constant rate until 2023

The projected cost of applying the techniques is also given in sheet CV103.

6.6.7 Investment Costs

The table below shows the costs associated with the selected investment techniques.

Costs from CV103 ED1 submission

Secondary network Cost (£m)	2015	2016	201 7	2018	2019	2020	2021	2022	2023	DPC R5	RIIO-ED1
Active Network Management - Dynamic Network Reconfiguration	-	-	-	-	-	-	-	-	-	-	-
Flexible AC Transmission Systems	-	-	-	-	-	-	-	-	-	-	-
D/GSR	-	-	-	-	-	-	-	-	-	-	-
Embedded DC Networks	-	-	-	-	-	-	-	-	-	-	-
Enhanced	-	0.00	0.00	0.00	0.01	0.01	0.02	0.02	0.02	-	0.1

Secondary network Cost (£m)	2015	2016	2017	2018	2019	2020	2021	2022	2023	DPC R5	RIIO-ED1
Automatic voltage Control (EAVC)											
Fault Current Limiters	-	-	-	-	-	-	-	-	-	-	-
Generator Providing Network Support	-	0.01	0.01	0.02	0.04	0.07	0.09	0.12	0.14	-	0.5
Intelligent control devices (EVs)	-	-	-	-	-	-	-	-	-	-	-
New Types Of Circuit Infrastructure	-	-	-	-	-	-	-	-	-	-	-
Meshing (permanent)	-	0.16	0.17	0.33	0.65	0.98	1.30	1.63	1.96	-	7.2
Meshing (temporary)	-	0.02	0.02	0.04	0.07	0.11	0.14	0.18	0.22	-	0.8
Real-Time Thermal Rating	-	0.09	0.09	0.18	0.35	0.53	0.71	0.91	1.11	-	4.0
Switched Capacitors	-	0.02	0.02	0.03	0.06	0.09	0.12	0.15	0.17	-	0.7
Conventional reinforcement	-	1.67	1.66	3.29	6.52	9.70	12.83	15.91	18.95	-	70.5
Electrical Energy Storage	-	-	-	-	-	-	-	-	-	-	-
Smart Enabler	-	0.13	0.14	0.27	0.52	0.78	1.04	1.30	1.56	-	5.7

Solution	Percentage of ED1 Transform Solution Spend *	Percentage of FALCON spend to 2020
Conventional reinforcement	84%	98
Meshing (permanent)	9%	1%
Real-Time Thermal Rating	5%	1%
Meshing (temporary)	1%	
Switched Capacitors	1%	
Generator Providing Network Support	1%	
Enhanced Automatic voltage Control (EAVC)	0%	
Active Network Management - Dynamic Network Reconfiguration	0%	
Flexible AC Transmission Systems	0%	
D/GSR	0%	

Solution	Percentage of ED1 Transform Solution Spend *	Percentage of FALCON spend to 2020
Embedded DC Networks	0%	
Fault Current Limiters	0%	
Intelligent control devices (EVs)	0%	
New Types Of Circuit Infrastructure	0%	
Electrical Energy Storage	0%	

*Excludes Enablers

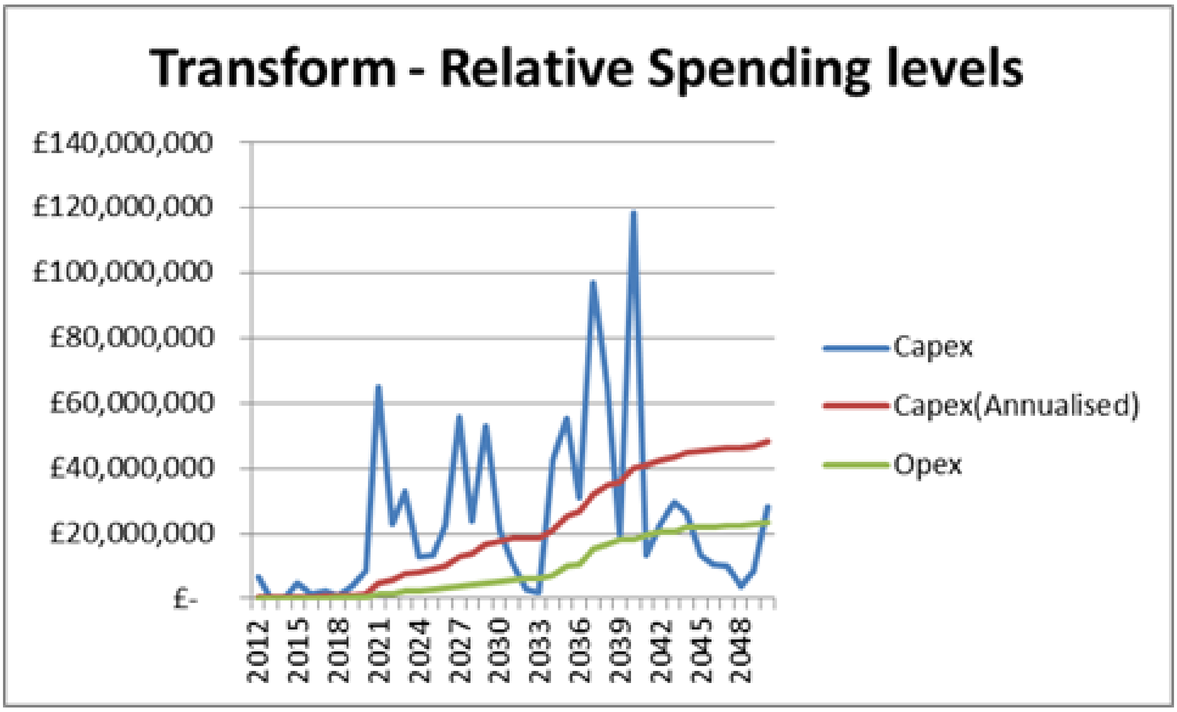
The split between investment spend differs from the number of installations with traditional reinforcement accounting for an even larger share of the expected investment. This reflects that the average cost of reinforcement is higher than the average cost of the other techniques.

The view from FALCON puts even more emphasis on traditional reinforcement though that may be explained in part by the large volume of remedial work given in 2015 which has been restricted to traditional reinforcement only and that the comparator runs extend only to 2020 rather than 2023.

The WPD best view has lower numbers of installations than the DECC 1 scenario outputs and therefore suggests a lower total spend over ED1 of approximately £90 million as opposed to £128m suggested by the DECC 1 scenario, however the proportions of installations and proportions of spend are identical for the DECC1 scenario outputs and the WPD best view.

6.6.8 CAPEX/OPEX Split

Figure 57: Transform Model Relative Spending



Source: <Insert Notes or Source>

The chart above uses data from the Results Input sheet which where the Transform model outputs are fed into the ED1 planning spreadsheets. This shows the variable nature of CAPEX expenditure.

The annualised version smooths these differences out, which reflects the approach taken in the regulatory treatment of CAPEX with recovery being smoothed by the Regulatory Asset Value mechanism. After an initial period of relatively high CAPEX, the ratio between Annualised CAPEX and OPEX stabilises with the OPEX being between a half and a third of the Annualised CAPEX

This suggests that while CAPEX is also sporadic in nature the OPEX costs associated with the new techniques soon increase to a level that is comparable with the annualised CAPEX. This may be because FALCON has included the ongoing maintenance costs for all new assets that are installed, to enable a fairer comparison with DAR, DSM and DG but it is unlikely that they have been included in Transform.

6.6.9 Solution Benefits

The table below shows the expected benefits for solutions applied in the Transform Model. For example, applying Dynamic Network Reconfiguration (Automatic Load Transfer) is expected to release 30% headroom for cables in relation to thermal limits and release an additional 3% voltage headroom.

Benefits assigned to Solutions within the Transform Model	Benefits					
Solution	Thermal Transformer	Thermal Cable	Voltage Headroom	Voltage Legroom	Power Quality	Fault Level
Dynamic Network Reconfiguration - HV	10%	30%	3%	3%	5%	0%
DSR_DNO to Central business District DSR	5%	10%	0%	3%	0%	0%
DSR_DNO to aggregetor led HV commercial DSR	5%	10%	0%	2%	0%	0%
DSR_DNO to HV commercial DSR	3%	5%	0%	1%	0%	0%
Electrical Energy Storage_LV connected EES - large	0%	0%	0%	0%	0%	-10%
Electrical Energy Storage_LV connected EES - medium	0%	0%	0%	0%	0%	-8%
Electrical Energy Storage_LV connected EES - small	0%	0%	0%	0%	0%	-5%
Permanent Meshing of Networks - HV	15%	50%	0%	2%	20%	-33%
RTTR for HV Underground Cables	0%	10%	0%	0%	0%	0%
RTTR for HV/LV transformers	10%	0%	0%	0%	0%	0%
HV underground network Split feeder	0%	100%	1%	2%	0%	0%
HV underground New Split feeder	0%	80%	1%	1%	0%	0%
HV overhead network Split feeder	0%	100%	1%	2%	0%	0%
HV overhead New Split feeder	0%	80%	1%	1%	0%	0%
LV Pole mounted 11/LV Tx	80%	0%	1%	6%	0%	-10%
LV Ground mounted 11/LV Tx	80%	0%	1%	6%	0%	-10%

It was not possible to create comparative figures from FALCON due to the way in which it operates. Voltage and thermal headroom are calculated for each asset to determine if there are issues. However when issues are resolved this data is used within IPSA but not written to the results database so while the “before” values are known the “after” values are not.

Similarly FALCON only calculates network state metrics for healthy Network States. There may be several techniques applied between healthy Network States and therefore disaggregating the combination to improved metrics from each element is often impossible.

The “usefulness” of a technique can be considered in terms of the number of problems (either individual network issues or asset groups affected by at least one issue) that are resolved or prevented and the length of time for which they are resolved or prevented.

Even this measure is problematic because the SIM acts to resolve issues in the year in which they first appear. If the load scenario includes a more dramatic increase in load between years then more issues will arise in a year because more half hourly periods will exceed the threshold value. In the case of replacing a transformer this might resolve a single issue or multiple issues depending on the load scenario which may make one instance seem better value for money. What is not known is the number of issues that would have arisen in following years that have been prevented. This would require the SIM to have the facility to remove patches to determine the issues that would have been present, but where patches affect connectivity or overlay each other than this would result in unrealistic views of the network.

The number of asset groups that benefit from a technique will largely reflect the way in which the technique works and may not offer a fair comparison for effectiveness. For example a transformer replacement is unlikely to resolve issues on other asset groups that the transformer, whereas solutions which affect the whole feeder such as meshed network, splitting the feeder or creating a new feeder are very likely to resolve multiple asset group issues. The apparent difference in number of the number of asset groups that benefit from application of the technique is only relevant in subsets where a choice can be made and one technique can substitute for another.

In terms of the duration of the benefit from applying the technique, this is also difficult to determine a useful metric for. We can calculate how the mean duration from applying a technique which resolves the last remaining issue in a year to the time at which a new issue affects the same feeder, but this will be affected by the initial state of the network and previous investment.   While it may be possible to determine if an asset that has an issue resolved goes on to experience that issue again at a later stage, this is dependent on issues repeating within the timescales of the simulation and is likely to only apply to a few assets.

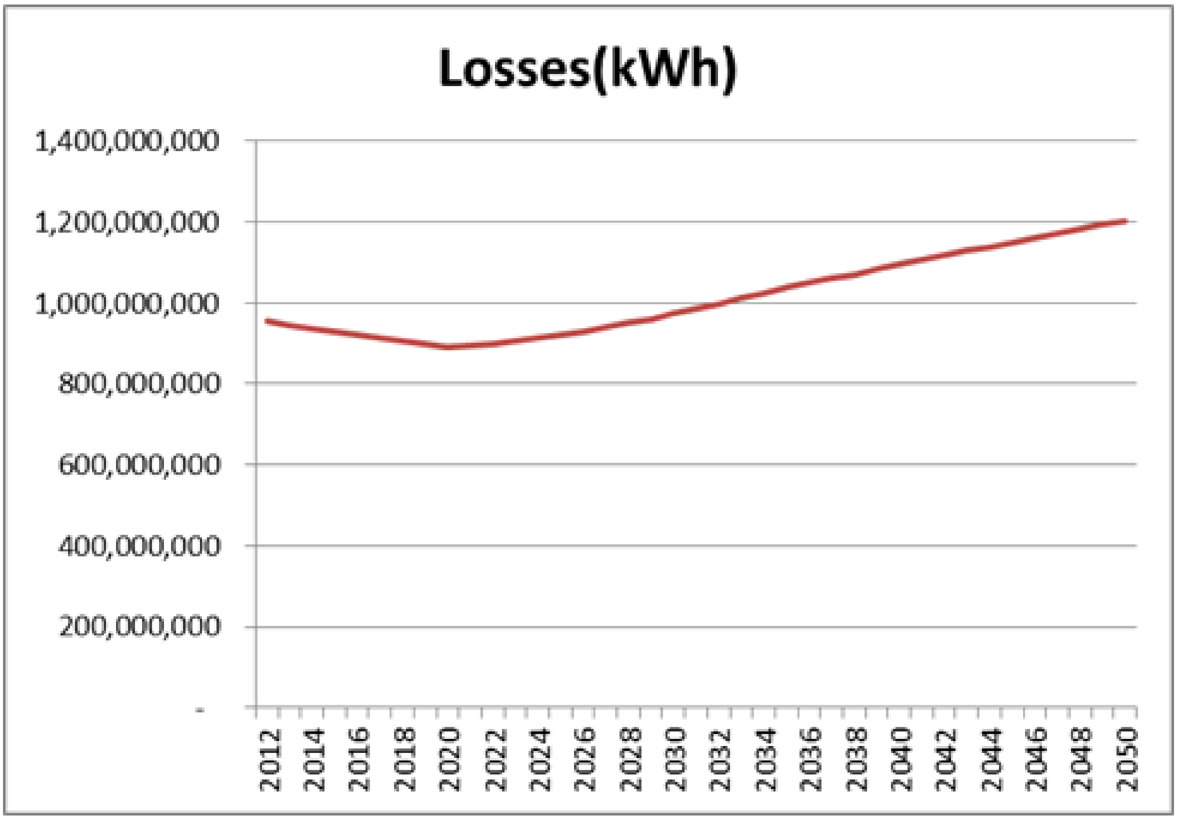
This suggests the best means to evaluate the value for money of having a technique is by taking a more general approach and relying on the technique benefits driving the A* search to find better solutions.

Rather than carrying out Runs that include a specific technique in addition to traditional reinforcement, it might be better to compare runs with all techniques to Runs that omit that particular technique.

Such Runs were not part of the original specified set but would be a useful addition.

The Transform Model suggests that with the given load profiles and solutions selected the losses will initially reduce with the minimum occurring in 2020 representing a 4% reduction on the 2015 value, before increasing steadily with the 2050 value being 29% higher than the 2015 value.

Figure 58: Transform Model - Losses



Source: Transform model

An increase in losses is also anticipated by FALCON with increasing values of cable utilisation.

6.7 Overall Investment plan and expected benefits

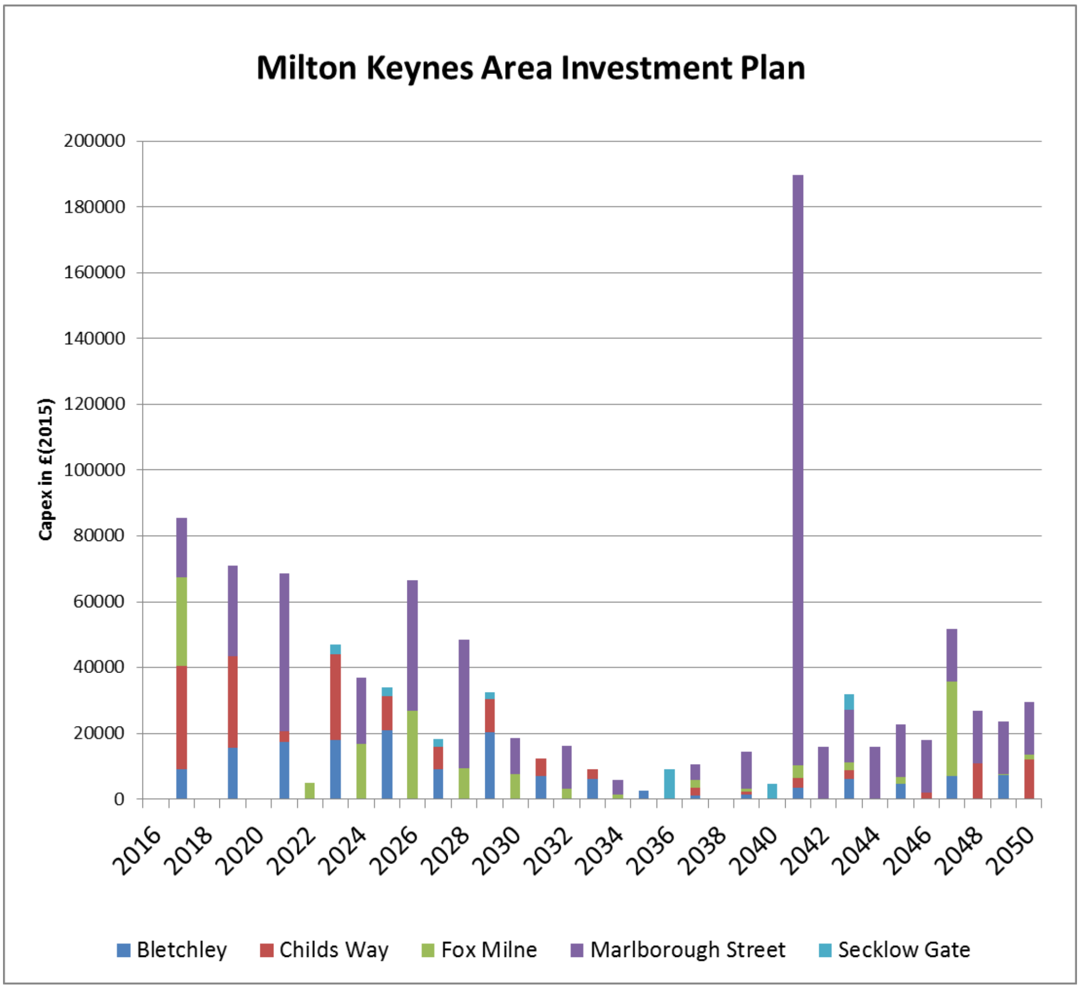
The investment plan below is drawn from the average capital expenditure values for results for each Primary for DECC1. (An exception is Bletchley where DECC2 results have been substituted due to DECC1 results not being available) Values in the table reflect that future values have been discounted to their 2015 value.

All values in £ k (2015 prices)	Bletchley	Childs Way	Fox Milne	Marlborough Street	Secklow Gate	Total
2015	1,794	1,062	91	1,916	-	4,863
2016	-	-	-	-	-	-
2017	9	31	27	18	-	85

All values in £ k (2015 prices)	Bletchley	Childs Way	Fox Milne	Marlborough Street	Secklow Gate	Total
2018	-	-	-	-	-	-
2019	16	28	-	28	-	71
2020	-	-	-	-	-	-
2021	17	3	-	48	-	69
2022	-	-	5	-	-	5
2023	18	26	-	-	3	47
2024	-	-	17	20	-	37
2025	21	10	-	-	3	34
2026	-	-	27	40	-	66
2027	9	7	-	-	2	18
2028	-	-	9	39	-	49
2029	20	10	-	-	2	32
2030	-	-	7	11	-	19
2031	7	5	-	-	-	12
2032	-	-	3	13	-	16
2033	6	3	-	-	-	9
2034	-	-	1	4	-	6
2035	3	-	-	-	-	3
2036	-	-	-	-	9	9
2037	1	2	2	5	-	10
2038	-	-	-	-	-	-
2039	1	1	1	11	-	14
2040	-	-	-	-	5	5
2041	4	3	4	180	-	190
2042	-	-	-	16	-	16
2043	6	2	2	16	5	32
2044	-	-	-	16	-	16
2045	5	-	2	16	-	23
2046	-	2	-	16	-	18
2047	7	-	28	16	-	52
2048	-	11	-	16	-	27
2049	7	-	0	16	-	24
2050	-	12	1	16	-	30
total	1,951	1,220	229	2,477	28	5,905

The investment in 2015 is the largest component of the investment plan. This suggests there is a need to further analyse the 2015 load values. The total capex spend profile is shown in the chart below with 2015 omitted for clarity. The variation between years is significant with the investment in 2042 for Marlborough Street being larger than the combined investment in other years.

Figure 59: Milton Keynes Area Investment Plan



Source: FALCON Project Data

Comparing expected plans for DECC1, which is one of the more demanding scenarios, and DECC4 which has the least increase in load growth, suggests an overall difference of around 10% in terms of additional costs. However these vary considerably between Primaries.

Scenario Comparison All values in £k (2015)	Bletchley	Childs Way	Fox Milne	Marlborough Street	Secklow Gate	Total
DECC1	1,926	1,220	229	2,397	28	5,800

Scenario Comparison All values in £k (2015)	Bletchley	Childs Way	Fox Milne	Marlborough Street	Secklow Gate	Total
DECC4	1,881	1,125	124	2,107	6	5,242
Additional costs for DECC1	44	96	105	290	23	558
Percentage increase for DECC1	2.30%	7.83%	45.88%	12.10%	79.59%	9.61%

Comparing Runs with and without smart techniques suggests a very variable picture in terms of financial benefits. Including smart techniques has the effect of reducing capex while increasing OPEX.

The net benefit in TOTEX is 30% for the primaries in the sample but within the sample there is a wide range of saving from 3% to 41%.

TOTEX All values in £k (2015)	Bletchley	Childs Way	Fox Milne	Marlborough Street	Secklow Gate	Total
DECC4 traditional only costs	2,809	1,254	274	3,824	7	8,168
Decc 4 all techniques cost	2,064	1,222	173	2,267	6	5,732
saving	745	32	102	1,557	1	2,436
Percentage saving	27%	3%	37%	41%	11%	30%

This value is significantly higher than that suggested by the 2020 analysis of 6% which was based on a single primary compared for a five year period. This saving is likely to be reduced by adopting wider tolerances on issues. i.e. this assumes transformers are replaced once they are more than 1% overloaded and therefore the savings from DAR are likely to be greater than if the issue threshold were set at 10% The variation between primaries suggests that generic modelling with all primaries being able to benefit equally from techniques, could be improved by including additional factors, such as initial load indices, into account. This would be a suitable subject for future investigations.

6.8 Deductions from SIM Experiment Results – Rules of Thumb

An initial project objective for FALCON was that the data mining of large volumes of results from SIM experiments would allow the project to determine "rules of thumb" that could be shared with other DNOs. These rules of thumb can be expressed in two different ways:

1. What is the best way to solve this type of problem?
2. What are the criteria that need to be met to ensure applying a given technique will provide value for money?

The intention was that these would be used to pass on learning from the SIM as planning guidance so that planners could decide whether or not to use techniques without having to use a planning tool with complex power analysis facilities which can also model all the other techniques. The SIM is the only example of this level of functionality and while a modified version of IPSA may make this more available to other DNOs the aim was to provide a quick mechanism to support decision making.

- While the SIM can certainly provide useful information to help assess the techniques overall, it is no longer considered that these can provide sufficient information to remove the need for a sophisticated planning tool. Providing rule of thumb may not be appropriate or possible. The learning that has been derived from the SIM for the smart techniques is summarised in the following sections.

6.8.1 Dynamic Asset Rating (Transformer)

The trials have already suggested that because of the higher temperatures in enclosed substations that the location of the transformer is the most significant factor in the degree of additional headroom that is found by carrying out this more sophisticated assessment of capacity. In this case we know what asset types will be affected by applying the techniques. This can only resolve issues in transformers and cannot have any impact on thermal or voltage constraints in linear assets. This is chosen frequently by the SIM as the costs are relatively low. The A * search has been seen to optimise correctly with traditional reinforcement preferred to DAR where subsequent reinforcement was required within two years. Further work could include an analysis of sensitivity to threshold levels for issues i.e. to what extent is the benefit of DAR reduced if the threshold for thermal issue is set to 5% rather than 1%.

6.8.2 Dynamic Asset Rating (Cable)

Once again no analysis is required to establish that this technique can only resolve thermal issues on underground cables. There is no spin-off benefit to other parts of the network from applying this technique. The key factors for effectiveness are known from the algorithm used for modelling so there is no need to derive these from data mining, i.e. that this will be limited by cables running close to each other or in ducts and will reflect the type of cable. e.g. single cores or composite segmented cable. Again the key sensitivity for DAR in cables may be the thermal issue threshold.

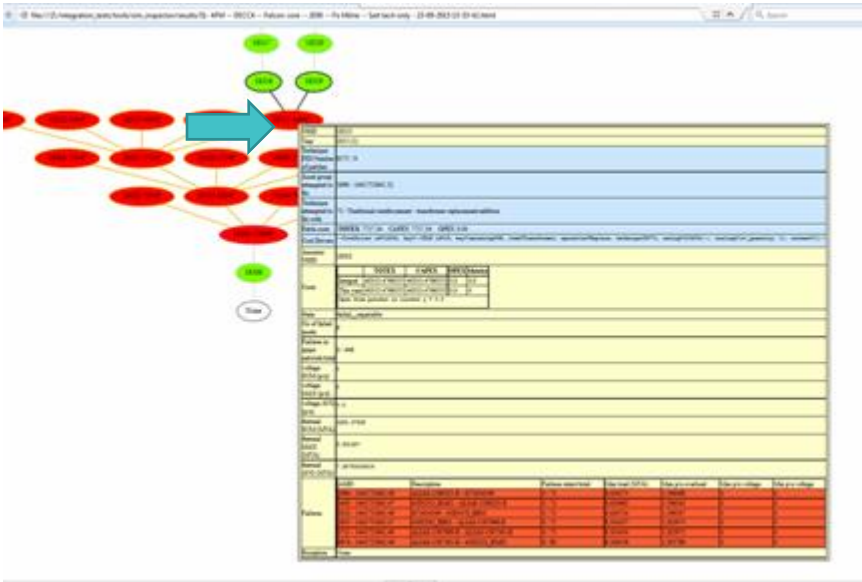
6.8.3 Automatic Load Transfer

- ALT was not assumed to be applicable for resolving N-1 conditions because the network would be undergoing a rapid process of reconfiguration due to fault location and restoration activities and an automatic scheme would most likely be disabled in this case. ALT employs similar logic to that used for assessing the network loading under N-1 conditions and therefore does not enable more complex switching than is assumed under N-1 conditions both algorithms attempt to redistribute load as favourably as possible between the normal open points that are available.
- As loads increase, thermal issues arise under N-1 conditions before they affect the intact network. While it is possible for networks to have issues under normal running as well as under N-1 conditions, there have been no instances observed where a network has a thermal issue under normal Running conditions but not under N-1. Therefore the techniques which resolve thermal issues under N-1 conditions prevent these from worsening and affecting the intact network and therefore ALT is not selected.
- Having thermal issues on an intact network but not under N-1 conditions would be possible if the remedial actions for N-1 conditions were not available under normal Running e.g. if Demand Side Management were only envisioned as a post fault service and not to operate routinely. In those circumstances then ALT would be able to contribute to resolving network issues. Similarly other techniques such as using DG or commercial use of batteries owned by a third party, could be restricted to post fault use only.
- ALT was expected to be able to resolve voltage issues on the intact network. (Voltage issues under N-1 conditions are not considered by the SIM)
- The opportunities for ALT have been very rare, with voltage issues being relatively rarely observed.
  While other techniques have been applied in an attempt to resolve voltage issues, this has not been the case for ALT , even in situations where it would appear to be a reasonable solution. This is the subject of ongoing investigation, however it is clear that the benefits will be very specific to the network and the existing techniques that are applied. This suggests a rule of thumb approach is unlikely to be useful and that full power flow analysis that includes the ability to model other mitigating techniques will really be the only means to determine whether the application will be value for money.
- The existing version of the SIM focuses on optimising a long term plan for load related reinforcement. This is unlikely to capture all the benefits of having a more flexible network with greater automation and remote control which enable better optimisation of the network in real-time.

6.8.4 Meshed Networks

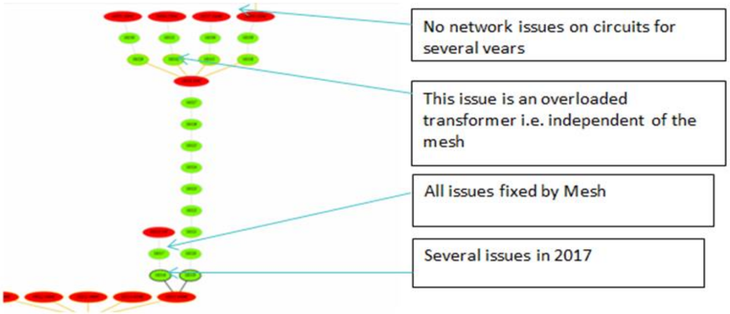
- The results from the SIM show that meshed networks can provide a cost effective means to manage network issues with positive spin off benefits for CMLs, CIs and losses.
  However, it is clear from the trials that meshed networks will not automatically provide these benefits and the success will depend on the relative impedances at various points. This suggests that a rule of thumb approach is also unlikely to be a good substitute for modelling meshed networks in a power flow tool.
- For Experiment 34 at Marlborough Street for DECC1 we can see how the creation of a mesh is followed by several years of issue free operation in comparison to the same network with traditional reinforcement only. The network has a number of thermal issues in 2017 as seen by the list of items coloured red in the detail window.

Figure 60: Marlborough Street- DECC1



- After the mesh is applied there are several years without issues on the feeders

Figure 61: Application of Mesh



Source: Project FALCON

This example of a meshes at Fox Milne shows the operation of the A* search. A meshed network is preferred to an instance of DAR, which has lower initial costs but though cheaper, does not resolve issues for long.

6.8.5 Storage

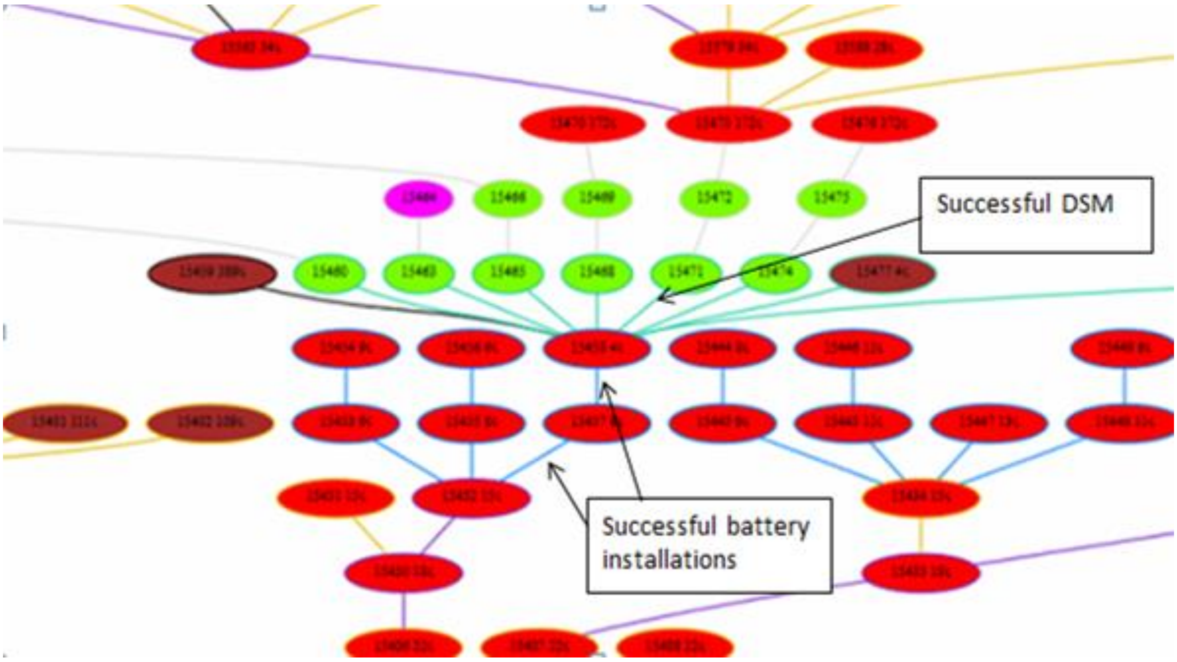
Due to the expense, storage is not often the solution chosen to resolve network issues within the SIM. This leads to insufficient data from which to extract rules of thumb with any confidence, other than “batteries are used when there are no other options”.

Batteries have been applied for both thermal and voltage issues which they have been able to resolve.

As storage cost is the main obstacle to the application of this technique, there will be a Run in the sensitivity analysis work which will include a lower battery cost to determine the increase in usage at a lower cost.

The tree view below shows two instances where batteries have been installed to resolve voltage issues.

Figure 62: Result Tree View/Batteries



Source: Project FALCON

6.8.6 DG / DSM

DSM was seen to be applied within the SIM and was seen to improve the network after being applied. However this was also a relatively rare occurrence compared to DAR or Meshed networks, so there is insufficient data to extract rules of thumb using a data mining approach. The success of this technique is driven by the assumed resources available in the local areas and the scale and duration of the network issue which are both highly specific to location and scenario, and so require the level of detailed modelling that is provided by the SIM. No examples of DG were seen but as the technique could only be applied where distribution substations were known to have suitable generation, suitable sites for the technique are rare.

6.8.7 Traditional reinforcement

Large number of potential upgrades for transformers. Most of these patches are not carried forward and there seems to be a random element in patch creation that could be improved with further analysis. This should not block off investment ahead of need as an option, but there is room to improve the order in which patches are applied.

6.9 Key Conclusions

Referring back to the Introduction to this document, the project set out to address these main high level objectives:

1. Is it possible to improve 11kV planning?;
2. Can a single tool support both strategic and business planners?;

3. What new data does a DNO need in a low carbon world?;
4. What are the algorithms, assumptions, simplifications that have been used and how could these be improved in future releases?;
5. How do we managing data from legacy systems and address challenges in migration?;

6.9.1 Is it Possible to do improve 11kV Planning?

To address this question it is necessary to firstly outline the current 11kV planning process. This is not detailed by step by step planning process to cover all possible situations, but rather is covered by two main Business policy documents:

- SD1/2 “Relating to the Fundamental Aim and Structure of WPD System Design Policy”. This document defines the fundamental aims.
- SD4/5 “Relating to 11kV and 6.6kV System Design” This document describes the standard requirements for the design of the 11kV and 6.6kV systems.

These processes are backed up by a series of *Standard Techniques* dependant on the particular circumstances of the enquiry or the area being considered. The overall result is a framework which ensures adherence to regulations while offering guidance to the planner.

The main benefits of the SIM for the Planning Engineer would be the provision of a PSA tool that comes complete with the 11kV Authorised Network Model already loaded and which would also give the planning engineer the ability to confirm the longevity of the design solution he/she has chosen for a new load connection by evaluating the network over time and with a number of alternative strategies and scenarios prevailing. At present much time and effort is consumed by the planning engineers obtaining accurate and complete network information for the area under consideration, perhaps as much as three times as much effort being expended in this direction than that actually spent in actually doing the analysis.

The 11kV planning engineers seldom look beyond a time horizon of five years, but even up to this sort of limit the SIM can still project the results of the planning actions over a number of possible scenarios providing a much more informed view of what is likely to happen next given the actions taken.

One of our key conclusions therefore is that the SIM can be seen to add a capability which augments the current planning process rather than changing it in a fundamental manner.

Of course the planners may also be able to conduct their analyses in an environment where a number of likely future scenarios have already been evaluated by the SIM from a strategic point of view, giving guidance on where hotspots may be likely to occur in the future and indicating what reinforcements (or other remedial actions) are likely to be needed. The picture is therefore one of a more informed backdrop to the planning process.

For a more complete answer to the main question, a deeper assessment of the SIM would be needed with actual business users making particular use of the Manual Patch application process expected to form the basis of the 11kV planning process for introducing new network changes. It might also be foreseen that the 11kV planning engineer would potentially want to interactively adjust the loads at specific network locations outside the current "demand scenario" based approach to network wide application of actual load evolution scenarios, essentially to see how the network responds to specific load affecting events or conditions (expansion of a factory perhaps).

The use of automatically applied techniques for longer term planning could be extended to provide a degree of automation for other planning work such as new connections, cable diversions, undergrounding etc. These would involve more complex rule sets and would need to be supported by an even richer data set than the current Authorised Network Model and may only be used to provide preliminary plans to be finalised by the planners. However, given the large volumes of new connections, even partial automation of the process would be beneficial.

6.9.2 Can a single tool support both Strategic and routine Business Planning

WPD's current business model has separate roles for short term and long term planning. The FALCON project has from its outset reflected the difference between the strategic long term view and routine business planning methodologies and sees these as valid and complementary approaches to assessing and managing the network.

The SIM supports both types of planning, allowing the short term planner to take a more strategic view and the strategic planner pass on specifics of likely long term issues to the planners for each area.

11kV Planning Engineers are concerned with particular issues for which they need to find an appropriate response. They are not currently equipped however to assess global network matters over potentially long time ranges independent from a specific change request. Rather, this should already have been assessed by a *Strategic Planner* who will have prepared company or regional wide consistent guidance for the BAU process on the basis of a range of possible prevailing conditions and potentially giving worst case scenarios and appropriate responses which the 11kV Planner, assessing a particular case, may then utilise.

The current prototype version of the SIM can provide a longer term view of required investment under different load scenarios. At the same time it would require significant improvement to performance to make it a production tool for strategic planners. The time taken to perform a Run is long and so with a large number of primary substations to assess, this would be a very time consuming exercise, even if this were automated and shared between machines.

Not all of the many possible RUNs that cab be identified for the SIM have been executed at the time of writing of this Report. The issue is greatest where networks are starting 2015 requiring remedial work to be modelled. Investigations are ongoing but it is difficult to discern whether this is caused by problems with the software itself or that the SIM has been set an impossible task. Given the large increase in peak load for the load scenarios, and the limits imposed on traditional reinforcement (no more than two additional feeders per primary, no more than two additional cables along linear asset routes and no more than two additional transformers per substation), it is possible that the SIM has exhausted legitimate upgrade options. Improved logging and diagnostic tools would help with this assessment, though there is also a related issue of how far into the future a nodal modelling approach is suitable. For later years of the simulation, not only are the load estimates highly speculative but the network itself will have been transformed by the modelled upgrade work which includes adding and reconfiguring feeders. Even if we assume the load related reinforcement work is correctly anticipated, there will be new connections, diversions and other improvement schemes that reduce the likelihood of the nodal network model being an accurate representation. Similarly, the handling of asset groups, a key concept in the management of issues and patches, becomes more complex as more asset groups are altered by the application of patches to the network. Therefore the results for later years of the simulation, for example past 2040, may be more useful in terms of suggesting approximate volumes of work than they are at highlighting specific locations. For long term simulations there will be a point where nodal model analysis is no more accurate than more generalised models like Transform. Further work is recommended to determine the year in simulations at which the improved accuracy benefits of using a nodal model no longer outweighs the additional computational effort.

The use of the SIM by a Policy user seems less likely. It was originally postulated that a Policy user could test new techniques by commissioning a new Technique plug in and testing the difference in long term costs and metrics for the network with and without the new technique. The SIM development has shown that creating, testing and integrating Technique plug-ins is a far more complex and lengthy process than was originally anticipated. The process to develop and integrate technique plugins would need to be far simpler before this could be done speculatively rather than for techniques which were certain to be required for modelling.

6.9.3 New Data DNOs Need in a Low Carbon World

It should firstly be noted that the reference to 2013 dates back to the early period of the project, in fact it would be more correct to simply substitute “now” for “2013”.

It was already clear, prior to FALCON that emerging DNO tools, as well as those that will be required to support future systems, need a more extensive and “joined-up” approach to data management.

The data available to DNO’s at the current time is present in “Island” data repositories which support, and in many cases are embedded within, existing and distinct/separate tools. So it is not simply a question of what new data is required, it is more a case of there being a requirement for a new common data presentation layer to be available to the application layer which will use it. WPD is already looking at projects which will pull together multiple data sources to provide the INM (Integrated Network Model) data view of which the FALCON SIM Authorised Network Model is a clear prototype example.

Referring to Section 5 on the Authorised Network Model and also the sections of this document covering the intervention techniques, it is also clear that new data is required as well in order to provide a more complete network description and modelling capability. The requirement can also become rather extensive as increasing levels of complexity are pursued in the challenge of providing ever more accurate modelling capabilities.

Should it also be concluded by the business that Smart techniques do have a place in the network management strategy, then it will be necessary to collect and manage all of the associated data required to manage these. This would include cost data relating not only to the purchase (CAPEX) elements, but also ongoing OPEX costs for which there are no current values as there is no experience of Running these within the BAU process. OPEX includes not just the maintenance and management costs but also the peruse costs necessary to fully manage (and model) the assets in techniques such as DAR and Energy Storage.

For some items within the cost model, items of different capacity were allocated the same cost because the granularity of WPD cost reporting did not differentiate between the items. This is likely to distort the selection of items, automatically suggesting that the larger capacity version is better value for money. Therefore additional granularity around cost data may be required.

For Load Estimation, extensive data about properties and customers was used though this remained the property of third parties and was not directly visible. This data, or a similar approximation, is likely to be required by DNOs in the future.

6.9.3.1 Specific Conclusions

The project has concluded that the following are, or may be, needed to fully model or manage networks operating in the low carbon, smart-grid paradigm:

In the Real World:

- Real-time network data for energy storage systems (battery) management (requiring high bandwidth IP network communications capability);
- Potentially real-time network data for DAR asset monitoring unless a decision has already been taken to base operating margins on previously calibrated “like-systems” to those being Run to dynamic ratings. In situations where the modelled cases might digress sufficiently from the deployed instances, monitoring offers a capability to reduce risk of over driving the assets (because the ground is not as cool as expected or the exact type of equipment has not previously been calibrated for DAR).
- Where is DG on the network and how suitable is it for use – size, availability, notice;

- Where is DSM possible and again under what conditions.

For Modelling Purposes:

In the modelled world, such as that of the SIM, it is possible to propose network changes at a wide range of locations. In the real world however candidate locations may be inspected only when needed. Thus the modelling data requirements cover the whole network.

- More substation environment information for new equipment placement and upgrade purposes. Drives how the modelling tools make informed decisions;
- More complete electrical systems (equipment) information in order to be able to correctly model with confidence the same equipment for DAR purposes in particular. The DAR modelling algorithms require many levels of detail and construction particulars (oil volumes, types of insulation etc.) many of which are not readily available.
- Details of other environmental factors, including the weather (ambient temperatures, and potentially wind speeds, solar gain etc.) and factors such as soil types and soil moisture content as a function of time of year;
- Substation (other factors) such as proximity of housing (to determine suitability for battery placement) or available space, including legal rights over the local area;
- Mounting capability for poles – what can be added to .mounted on the pole safely;
- Other details such as the DSM/DG data noted above;
- Complete cost data for assessing the cost/benefits of intervention deployment.

Limitations

Some information may never be obtained easily – for example: how far underground cables are ducted along their length, proximity of other cables etc. To determine this would require close inspection of buried cables – which is simply not possible.

6.9.4 Algorithms, Assumptions, Simplifications Used

The algorithms, assumptions and simplifications have been described in detail within the relevant sections of this document. Future development suggestions are also made where these have been identified.

6.9.5 Managing Data from Legacy Systems

FALCON work carried out to derive the SIM network model (Authorised Network Model) representing the real world network, based on extant (legacy) system master data is documented in Section 5 of this report. One of the main project conclusions has been that an integrated network view is highly desirable and indeed a follow on project is under consideration within WPD to assemble an INM (Integrated Network Model).

6.10 SIM Performance Assessment

This section considers the measured performance of the SIM for the experiments conducted and considers this in terms of implications for future SIM developments.

Performance has been a constant consideration throughout the SIM development process on the FALCON project as it was known from the very start of the design process that the SIM would be processing time intensive due to the sheer number of evaluations needing to be done for even small network areas. One of the initial key design assumptions was therefore to optimise for performance where possible while concentrating effort initially into getting the functionality of the system in place. Bottlenecks and inefficiencies could then be “chased down” once an acceptable turn-around time had been obtained for the purposes of at least generating and analysing the main project reference Runs.

Based on these Runs conducted in pursuit of the FALCON objectives the project was able to make a number of conclusions and these are detailed in the next section.

SECTION 7

Conclusions Summary

This section summarises the main findings of the SIM project for the sections listed below.

- Section 3. Implementation of the SIM software system
- Section 4. Nodal Modelling of Evolution in an Electricity Distribution Network
- Section 5. Authorised Network Model Production
- Section 6. SIM Run analysis

Each of those sections has its own detailed conclusions section and includes recommendations for future work. This section is a broader summary.

7.1 Implementation of SIM Software System

The SIM consists of a Network Modelling Tool within a Simulation Harness with a middleware wrapper layer for data exchange between the two components. These worked together to allow experiments to be set up, executed and visualised using a Linux server and Windows client environments.

Very large volumes of input data were used with the network nodal model including six primaries but other network beyond the normal open points for those primaries outside of the core area. The resulting network model includes over a thousand distribution substations, with large volumes of accompanying load data for 36 years at half hourly resolution. Output data was no less significant and a file based data exchange mechanism was developed to avoid memory problems.

Automated testing was applied to the browser based GUI with integration testing building up through increasing levels of integration and complexity. This stage was highly iterative with many cycles of regression testing reflecting upgrades to software that came from new versions of the core product as well as bug fixing upgrades.

The project deployed a level of automated testing to ease the early stages of integration on the project. This included some GUI test automation tools. Integration testing followed more classic profile of assembling increasingly more complex component sets and testing these, though the SIMs own complexity levels leant themselves well to conducting tests at ever more increasing levels of integration. The path followed was incremental and iterative (repeating stages as necessary as bugs were found and cleared to ensure regression testing was carried out effectively) and included these main outline stages:

- To speed up testing an approach was taken to try to limit the elapsed SIM execution times by using a subset if the characteristic days. Reducing the half hourly periods used within the days was proposed but was not viable due to the technique processing dependencies.

- The design of existing Network Modelling Tools includes functionality to support constant user interaction which is not required for SIM usage. Similarly the current use of NMTs does not require the high level of robust performance necessary for the SIM. Reducing processing time supporting unused functionality and increasing the reliability of the NMT software would increase performance of the SIM.
- It was difficult to fully scope the work required at the start of the project before the design phase had determined the required functionality of the SIM. This resulted in some changes to responsibilities for functional elements. Despite having written interface specifications, this remained the most problematic area of the development.
- While collaborative working tools such as Bitbucket provided a good means to document issues, it was not necessarily the best means to achieve speedy resolution. The distance between the separate teams working in Manchester and Milton Keynes may have reduced the face-to-face working time. Combined working sessions and phone calls were seen to be more effective at resolving misunderstandings than written communications.
- Processes for code version control and deployment worked well, but the processes to provided data to the SIM such as load data, AUTHORISED NETWORK MODEL and Cost model information, while suitable to support a prototype, would require improvement for a production system.
- Performance is a key issue with the prototype taking considerable time to run an Experiment.
- While performance has been improved, the system would need further improvements to support use within the business. With several options for improving performance, this may be achievable.

7.2 Implementation of Nodal Modelling for Distribution Network

1. The future SIM requires an energy model that is scalable across a whole DNO region. This could be achieved by considering alternative sources for data to populate demographic attributes. Obtaining postcode level data rather than property level data may provide an acceptable trade-off between cost and accuracy.   Alternatively, subject to smart meter data aggregating rules, it may be possible to use smart metering data to identify customer archetypes from which occupancy and demographic data can be derived.
2. Performance could be improved by restricting the day types, limiting the variations in each technique application, adjusting the thresholds for issues.
3. Reporting requirements have changed for the ED1 price control period and so the sourcing of cost model data will need to be revisited. The prototype Excel tool requires further development, for example by developing a more fully integrated data management GUI, if it is to be used as a production tool. Sourcing data for new techniques, not covered by BAU reporting, remains an issue though the pool of

completed innovation projects that may provide reference data is increasing over time.

4. The size of the network model required to model the core six primaries within Milton Keynes is considerably higher than the core itself. In this case the total network required was three times the volume of the area of interest. This impacts on estimates for data volumes and number of busbars for the modelling tool. Analysing primaries one at a time allowed for faster processing times but resulted in new reporting requirements. Reporting investment on a “per feeder”, to enable overlaps to be understood and accounted for. While this involves greater post-run processing this is a benefit overall and the feeder level data is likely to be useful to the business.

   Trials feedback was often difficult to incorporate due to the different nature of information used for real time operation and planning, or a specific instance to generalised application;
5. Data analysis (especially during integration and validation testing) required the development of inspection tools external to the SIM in order to facilitate validation of the results generated by the SIM. Some of the functions of these inspection tools might be usefully incorporated into a future SIM version, but for the moment remain as peripheral support facilities;
6. While the entire FALCON area contained a balance of urban and rural networks, there were fewer overhead lines associated with the SIM analysis area. This reduced the opportunities for the SIM to demonstrate the management of voltage issues associated with long overhead lines present in rural areas. It is likely that this could only have been addressed with a much larger network model that covered a larger number of primaries.
7. The volume of data needed to support the SIM operation is very large indeed and an approach to its management for real-time access was needed to be derived to prevent out of memory conditions on the host platform. Careful consideration to data management will be required for scaling up the prototypes.

7.2.1.1 Further Techniques

The SIM currently implements seven techniques and these have been evaluated by the FALCON project (or in the case of traditional reinforcement, this is known from standard BAU processes). In terms of other new techniques, it is recommended that these should be drawn from projects where real world trials have already been carried out and cost data is available. Results from the analysis to date suggest that it would be useful to extend those that can be used to manage voltage issues, though to model these correctly may require the extension of the nodal network model to include LV and/or primary network.

1. If the SIM is considered to be fundamentally a tool for advanced optimisation based on nodal model analysis there is no reason to limit the SIM to only consider load related reinforcement techniques. So, for example, the SIM could be enhanced to include switchgear replacement techniques, asset health indices and their associated

fault probabilities and costs. By setting limits in terms of risk that encompass both risk of fault and the impact on the network of a fault in a particular location a reliability centred asset replacement programme could be developed. This could be optimised independently of the load related investment programme or the two areas of work could be considered together.

2. Techniques for losses reduction or network improvement could be modelled and optimised in the same way.

7.2.1.2 Future Adjustments Required in the NMT / NDM

There is a link between the performance of the SIM and the appropriate data handling. If concurrent analysis of larger sections of network is made practical by other performance improvements then this impacts on the data handling components which will then need to be scaled up. If the network will be analysed as a series of primaries then this suggests a different data handling approach needs to be developed to support that. Sensitivity analysis to the scale of the network area assessed is planned and will inform whether it is better to have fewer Experiments covering larger areas which take longer to complete or a larger number of Experiments covering smaller areas which complete faster and more reliably.

The existing Milton Keynes network as imported into IPSA has around 7000 busbars and is therefore within the limits of the current NMT which is set to handle over 20000. Scaling up the Milton Keynes network to cover all the East Midlands region, or all of WPD's operating areas would be beyond the current limit as it would represent a network with hundreds of thousands of busbars. While it may be possible to increase the limit on the number of busbars, from testing within the project, this would slow down the time taken to open windows, load and navigate network diagrams etc. to a level that would be unacceptable. As an alternative, it may be possible to create a set of network models for the user to select from that represent logical primary groupings for planning purposes. This would require the selection mechanism for network (the Network Data Manager) to have enhanced filtering facilities and a more complex mechanism to handle updates to assets in multiple network models.

Technique Data Inputs

- The DAR algorithm requires environmental inputs. In the SIM expected average values were used for weather variables and generic assumptions were made for soil parameters. For assessing DAR in real time there would be benefit in improving the data to allow more locationally specific values for soil conductivity. This reflects soil type but also moisture content which itself depends on recent rainfall, typical water table height etc. WPD's soil data obtained to support earthing calculations is not suitable for this purpose, but other aspects such as whether cables are ducted can be derived from the GIS data.

7.3 Authorised Network Model

The Authorised Network Model was successful in combining the asset and connectivity data from diverse sources to provide a unified network model for the SIM. This was achieved within the required timescales, budget and quality criteria. The approach used could readily be industrialised and scaled up to entire DNO regions and/or other voltage levels to provide high-quality modelling data and Common Information Model (CIM) interoperability. As the AUTHORISED NETWORK MODEL also supports a degree of data quality validation and mismatch resolution this is would also provide a good platform on which to base a Master Data Management solution for Network data.

Several additional datasets will be needed for Smart Grids, and these will also need to be appropriately managed and maintained within the overall Data Architecture. A better understanding of which data items the relevant modelling techniques are most sensitive to errors in is needed to identify which data aspects are worth investing in improvements to. Further research into this area would be valuable.

A two stage process is currently required to convert the WPD network data from corporate databases and systems such as PowerOn Fusion to the IPSA NMT file format. This requires importing data to an intermediate staging database (The Access version of the Authorised Network Model) followed by a Python scripted conversion to the IPSA i2f format.

Some parts of this process would require to be automated in order to better handle the larger data sets associated with the full DNO distribution network. This may include combining both stages into a single process and providing a mechanism to process only the data changes made since the last conversion.

A different network storage mechanism may be implemented for the NDM and NMT based on storing the network data in a database format instead of the text based i2f format. This would reduce the complexity of the conversion steps and the potential errors that they introduce. This would allow the NDM and the NMT to read network data and directly from the staging database or similar.

7.4 SIM Results Analysis

1. The SIM has successfully integrated a network modelling tool within a simulation harness with a complex exchange of data. The network modelling tool has been enhanced to extend power flow analysis from a single point in time to 48 half hourly periods over 18 representative day types for up to 36 years of analysis at the same time as incorporating new functionality to estimate the CMLs and CIs for the network in addition to the usual power flow analysis to determine voltages, current, losses and fault level. New modules have been included that allow for techniques to be applied to the network that involve determining appropriate locations, validating that the technique is beneficial and creating a patch so that the changes are incorporated in the network model.

2. The optimising process has been seen to operate correctly and has been extended beyond the initial A* functionality to include a learning element which improves performance through feedback.

   Effective tools for visualisation, bug tracing and reporting have been developed to complement the main GUI.

   The prototype SIM has been able to demonstrate a degree of complex data handling that exceeds the previous use of network modelling tools as an embedded component. Therefore it is not unexpected that there are some remaining issues.

The main benefits of the SIM for the Planning Engineer would be the provision of a PSA tool that comes complete with the 11kV AUTHORISED NETWORK MODEL already loaded and which would also give the planning engineer the ability to confirm the longevity of the design solution he/she has chosen for a new load connection by evaluating the network over time and with a number of alternative strategies and scenarios prevailing. At present much time and effort is consumed by the planning engineers obtaining accurate and complete network information for the area under consideration, perhaps as much as three times as much effort being expended in this direction than that actually spent in actually doing the analysis.

1. The 11kV Planning Engineers seldom look beyond a time horizon of five years, but even up to this sort of limit the SIM can still project the results of the planning actions over a number of possible scenarios providing a much more informed view of what is likely to happen next given the actions taken.
2. A key improvement to the prototype to assist 11kV planners would be to improve the user interface to provide an alternative to the geographic representation to make the connectivity and assets clearer. This would involve either replicating the existing schematic layout or creating a dynamic schematic representation that determines the optimum layout to represent the network selected. Such one-line diagrams are a feature of existing control systems.

The SIM could be used for strategic planning showing the longer term levels of load related reinforcement and the potential contribution from smart techniques. However further work is required to convert the prototype system into something that would be suitable for business adoption. These mainly relate to improving the speed at which the analysis can be completed but there is also some additional work to refine the calibration of load estimates to ensure these reflect the level of load reported by SCADA monitoring at feeder and primary level. Further work is required to determine the point at which the benefits of nodal network modelling (as opposed to more generic models) the additional processing no longer outweighs the additional processing overheads given the reducing confidence in both load and network data for later years.

The SIM has shown that traditional reinforcement techniques will account for the majority of network spend, but that the use of DAR and meshed networks will also be deployed to resolve network issues.

Thermal issues remain more prevalent in the medium term though some low voltage issues were observed after 2040 on some Runs. Large scale generation does not lend itself to modelling where prediction of likely size, type and location are required. Rather than complicate an already complex process further by repeated analysis to test different what-if analysis for large scale generation, another method needs to be developed to determine the impact of these connections on long term load related investment.

Batteries and Demand Side Management were seen to have relatively few applications due to the current price for batteries and the uncertainty around DSM availability. Sensitivity analysis to these factors and others is planned.

The inclusion of smart techniques has the effect of reducing CAPEX while increasing OPEX. A net benefit is seen in TOTEX of approximately 20% (subject to further validation) with improvements to network performance resulting from the adoption of meshed networks. Losses were seen to increase over the period due to network loads that increased over the period, with the peak load increasing by over 90% for some scenarios.

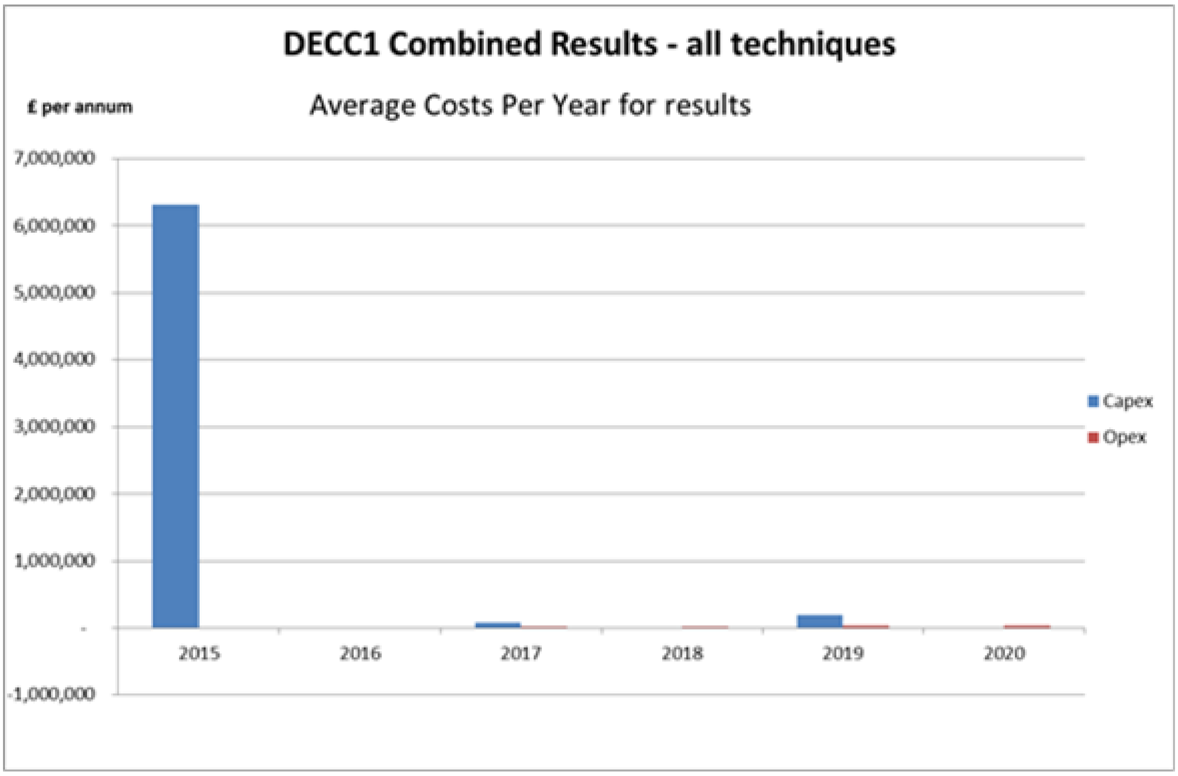
Appendices

A Extended SIM Results Analysis

A.1 DECC1 Scenario Investigation

The chart below shows that the majority of the capital expenditure occurs in 2015 to resolve the issues that are present when the network is first evaluated. After this there is expenditure in 2017 followed by a higher value in 2019. OPEX is relatively small in comparison.

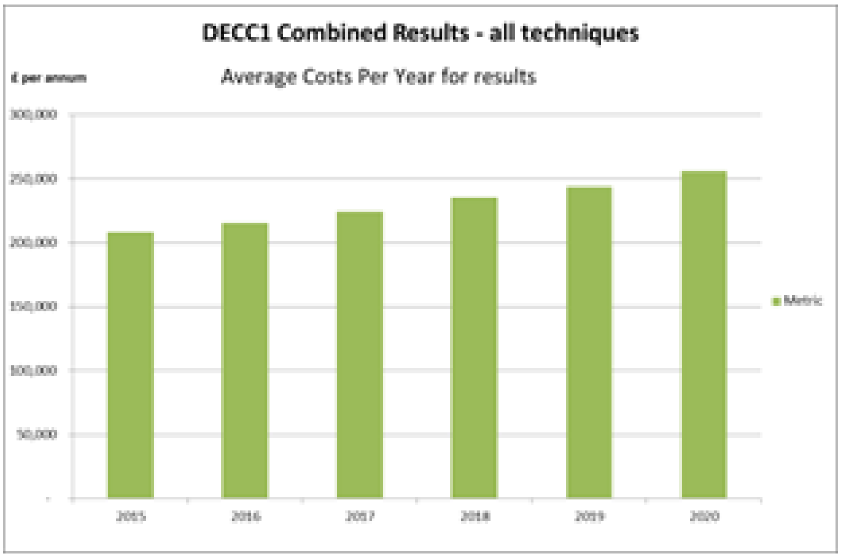
Figure 63: SIM RUN to 2020 DECC1 - Combined Results all Techniques



Source: FALCON SIM RUNs

Metric costs can be seen to increase uniformly during the period which is to be expected. Losses will increase as load profiles increase and CML/CI values have been assumed to increase over time.

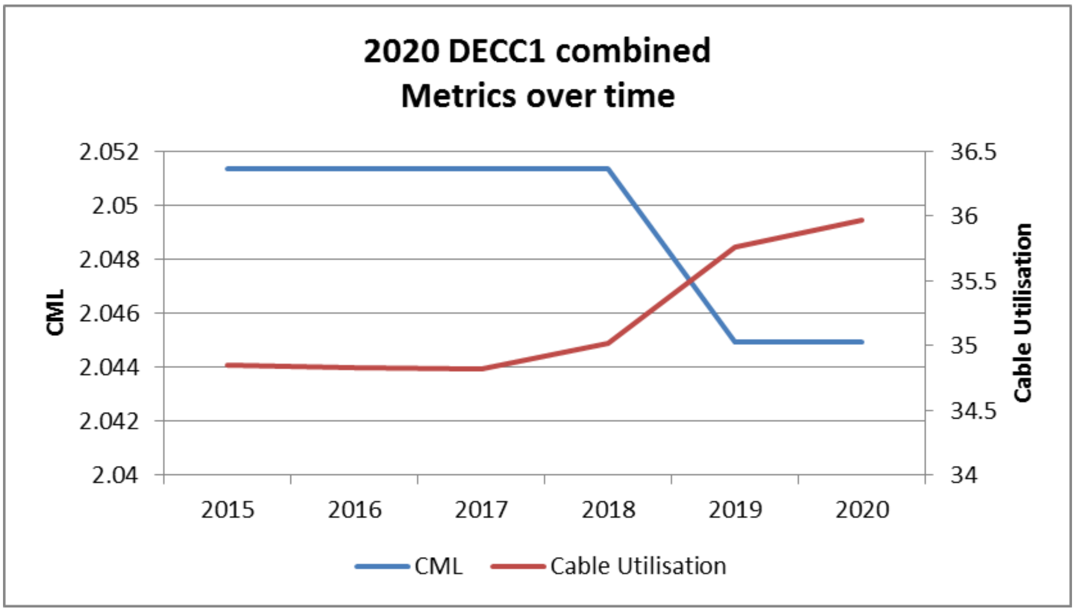
Figure 64: SIM RUN to 2020 DECC1 - Combined Results all Techniques - Metrics



Source: FALCON Project

Figure 29 below shows that while the CMLs reduce over time, as the result of applying mesh networks, the cable utilisation increases.

Figure 65: SIM RUN to 2020 DECC1 - Combined Results all Techniques - Combined Metrics



Source: FALCON Project

In terms of the techniques applied, the vast majority are traditional reinforcement with 72% of installations and 94% of the CAPEX cost relating to cable/ line upgrades. This is partly due to the restriction imposed that 2015 network issues will only be resolved using traditional reinforcement.

2020 DECC1 combined			
Technique Name	**Number**	**Proportion of Installations**	**CAPEX**
DAR(Cable)	11	16%	1%
DAR (Transformer)	12	0%	0%
ALT	21	0%	0%
Mesh	31	1%	0%
Batteries	41	0%	0%
DSM	51	0%	0%
DG	61	0%	0%
Transformer replacement	71	7%	4%
Cable / line upgrade	72	76%	95%
Transfer load to adjacent feeder	73	1%	0%
New feeder	74	0%	0%

A.1.1 Timing of Issues

A combined view of five primaries for 2015 has been derived covering the DECC1 Scenario. The plot is effectively a "heat map" showing the number of issues plotted per characteristic day (x-axis) and half hourly time slot (y-axis). This confirms that the peak days have a number of network issues, but in this case there are more network issues associated with winter weekdays and spring weekdays - with a large number for summer weekdays also being seen. It is also seen that the peak time of day is more likely to be morning than evening. Once the initial network issues are addressed, those manifesting in later years are likely to occur during the winter peak or spring weekday. Some characteristic days experience no issues (all green column on the plot). If this pattern is consistent across all primaries and scenarios then it would suggest that the performance of the SIM could be improved by removing the assessment of that particular day type.

Figure 66: Timing of Network Issues - 2015 (initial Year)

2020 DECC1 combined																		
Year	2015			Operating condition					n-1									
Settlement period	Spring Weekday	Spring Saturday	Spring Sunday	Summer Weekday	Summer Saturday	Summer Sunday	High Summer Weekday	High Summer Saturday	High Summer Sunday	Autumn Weekday	Autumn Saturday	Autumn Sunday	Winter Weekday	Winter Saturday	Winter Sunday	Winter Peak	Summer Peak	PV Peak
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	25	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	25	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	25	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	25	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	25	0	0
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14	0	0
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14	0	0
36	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
40	6	0	0	6	0	0	6	0	0	6	0	0	6	0	0	6	6	6
44	12	0	0	12	0	0	12	0	0	9	0	0	9	0	0	9	12	11
48	58	0	0	17	0	0	53	0	0	32	0	0	30	0	0	30	44	14
52	104	0	0	60	0	0	83	0	0	65	0	0	66	0	0	67	82	20
56	128	0	0	122	0	0	127	0	0	126	0	0	138	0	0	168	124	70
60	148	0	0	131	0	0	161	0	0	143	0	0	169	0	0	201	155	63
64	159	0	3	195	1	0	202	1	0	208	0	0	234	6	5	266	202	80
68	161	0	3	187	1	0	212	3	0	193	0	1	251	9	9	285	212	101
72	159	0	4	182	1	0	210	3	0	168	0	1	255	10	10	297	209	108
76	145	0	3	161	1	0	196	3	0	133	0	0	248	8	8	290	194	108
80	131	0	3	158	1	0	182	3	0	131	0	0	226	6	6	254	178	107
84	110	0	1	115	1	0	158	1	0	129	0	0	214	5	5	243	154	106
88	68	0	0	110	0	0	117	0	0	99	0	0	166	4	4	225	111	96
92	66	0	0	111	0	0	111	0	0	99	0	0	163	3	3	225	111	96
96	64	0	0	111	1	0	110	0	0	98	0	0	132	3	0	214	110	95
100	64	0	0	112	1	0	108	0	0	98	0	0	131	1	0	203	110	95
104	64	0	0	118	1	0	108	0	0	97	0	0	131	1	0	177	109	95
108	64	0	0	110	0	0	108	0	0	98	0	0	131	1	0	166	108	95
112	64	0	0	108	0	0	108	0	0	99	0	0	131	0	0	165	107	96
116	66	0	0	108	0	0	108	0	0	100	0	0	160	1	0	187	108	96
120	67	0	0	110	0	0	108	0	0	129	0	0	166	1	0	203	108	96
124	67	0	0	111	0	0	110	0	0	131	0	0	184	3	0	223	108	104
128	75	0	1	113	0	0	111	0	0	135	0	0	206	5	5	234	110	104
132	75	0	1	119	0	0	115	0	0	140	0	1	206	5	5	269	112	105
136	75	0	3	120	1	0	120	0	0	146	0	3	198	6	6	271	114	105
140	70	0	3	121	1	0	121	1	0	144	0	3	172	5	5	222	120	105
144	71	0	1	119	1	0	120	1	0	143	0	1	149	4	4	183	118	105
148	69	0	3	107	1	0	116	1	0	130	0	1	133	3	3	166	106	99
152	30	0	3	39	1	0	43	1	0	62	0	1	63	1	1	94	39	34
156	25	0	1	25	1	0	27	1	0	23	0	0	25	0	0	57	25	23
160	25	0	1	26	1	0	27	1	0	18	0	0	18	0	0	49	27	23
164	16	0	0	15	0	0	16	0	0	9	0	0	9	0	0	9	16	15
168	9	0	0	9	0	0	8	0	0	6	0	0	7	0	0	8	8	9
172	6	0	0	6	0	0	6	0	0	6	0	0	6	0	0	6	6	6
176	6	0	0	6	0	0	6	0	0	6	0	0	6	0	0	6	6	6
180	5	0	0	4	0	0	4	0	0	3	0	0	2	0	0	3	4	3
184	1	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	1	1
188	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
192	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 67: Timing of Network issues - 2016 - 2027

2020 DECC1 combined																		
Year	2016 to 2027				Operating condition						n-1							
Settlement period	Spring Weekday	Spring Saturday	Spring Sunday	Summer Weekday	Summer Saturday	Summer Sunday	High Summer Weekday	High Summer Saturday	High Summer Sunday	Autumn Weekday	Autumn Saturday	Autumn Sunday	Winter Weekday	Winter Saturday	Winter Sunday	Winter Peak	Summer Peak	PV Peak
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
52	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
56	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
60	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
64	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
68	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0
72	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0	0
76	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0
80	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
84	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
88	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
92	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
96	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
104	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
108	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
112	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
116	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
120	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
124	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
128	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
132	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
136	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0
140	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	0	0
144	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
148	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
152	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
156	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
160	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
164	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
168	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
172	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
176	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
180	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
184	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
188	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
192	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

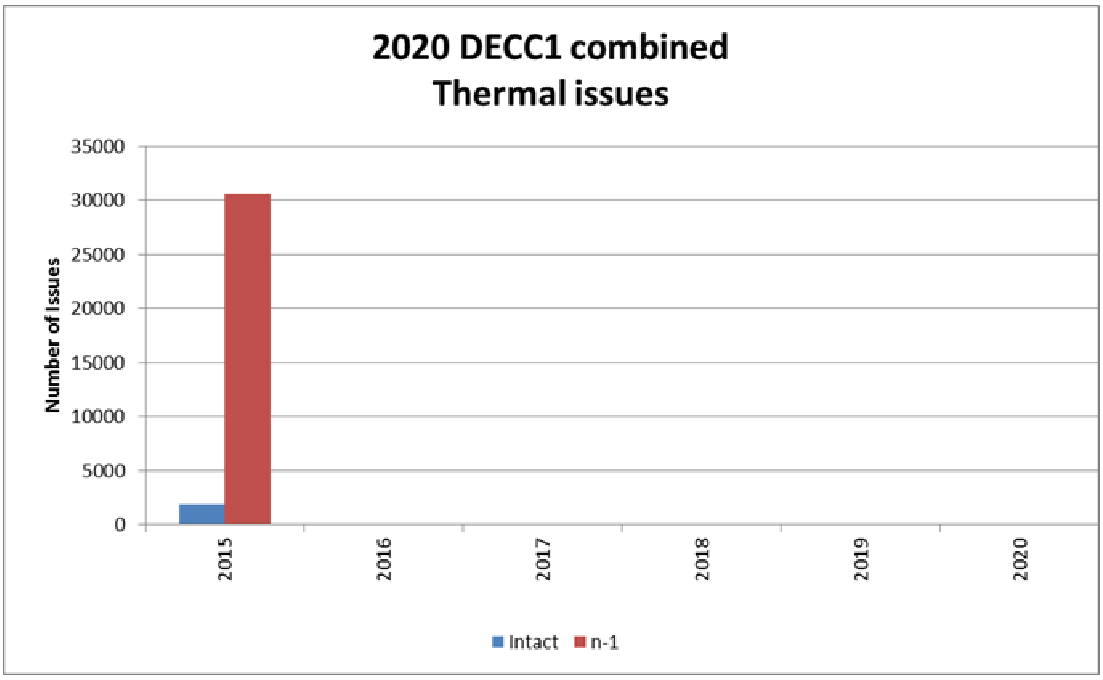
Source: FALCON Project

While some issues are present on the intact network, as expected they mostly occur under N-1 conditions.

A.1.2 Issues experienced

The following chart shows the distribution of thermal issues over the five year periods. While there are additional thermal issues in 2017 and 2019, these are not visible due to the scale which is driven by the high number of issues in 2015.

Figure 68: 2020 DECC1 Combined Thermal Issues

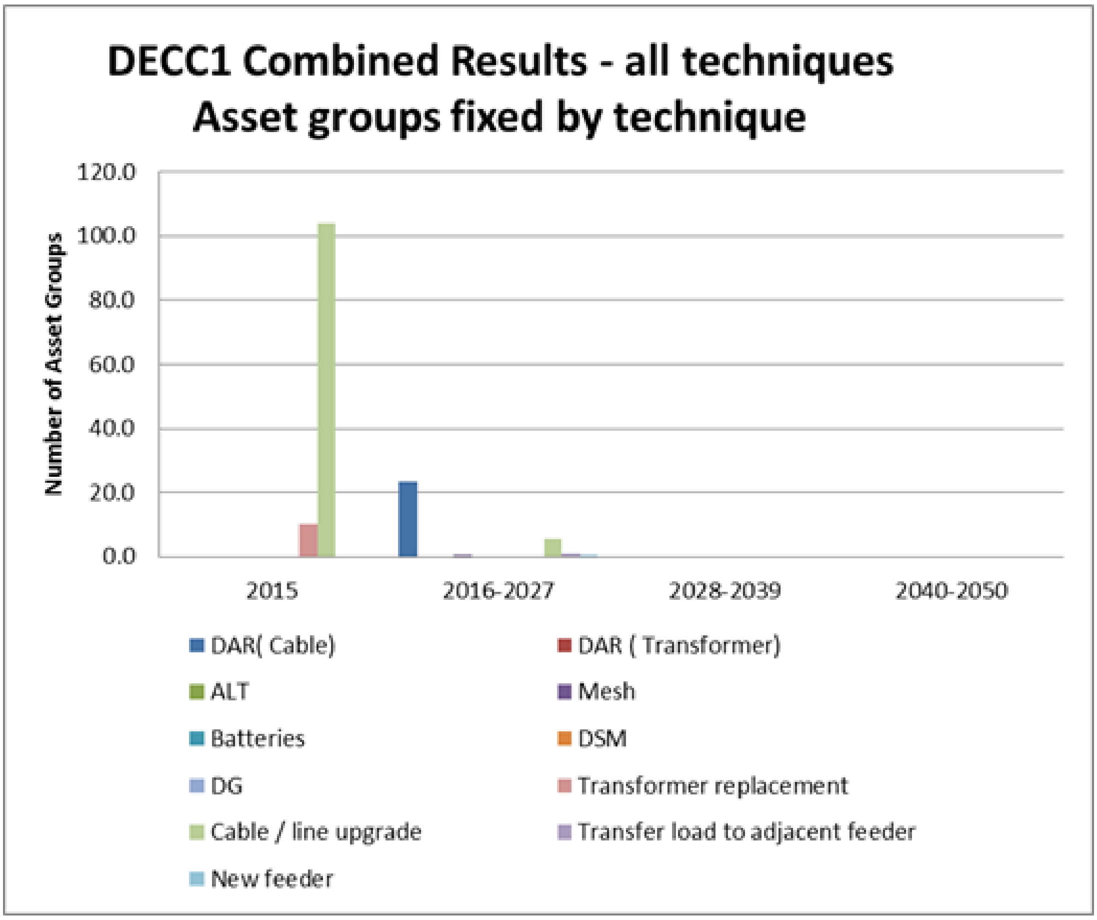


Source: FALCON Project

A.1.3 Technique Applicability

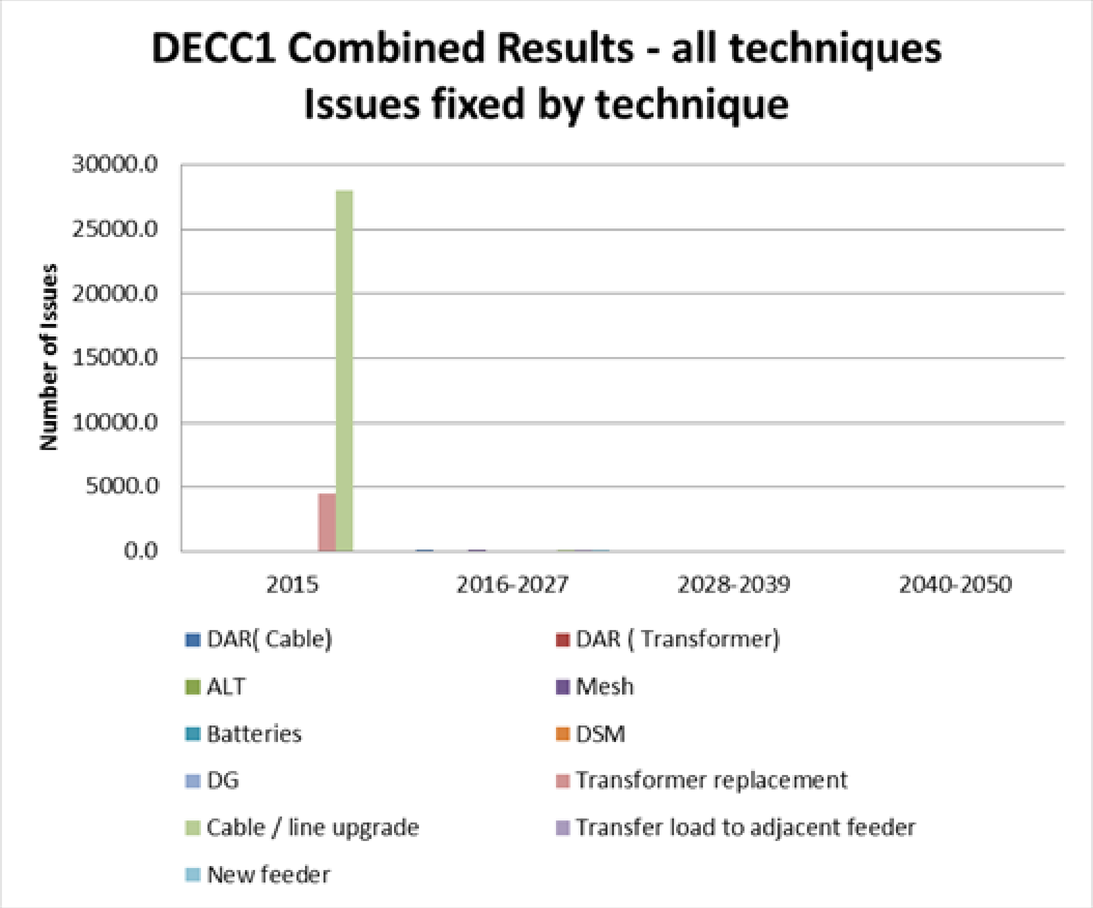
The following charts show that cable / line upgrade is responsible for fixing the majority of issues whether considered in terms of the number of asset groups fixed or the total number of issues. The higher proportion of asset groups than issues fixed by cable DAR suggests that it works well where the number of issues is limited. This is in line with expectations that it would not work for constant overloads where traditional reinforcement would be more applicable.

Figure 69: DECC1 Combined Results - Asset Groups Fixed by Techniques



Source: FALCON Project

Figure 70: DECC1 Combined Results - Issues Fixed by Techniques



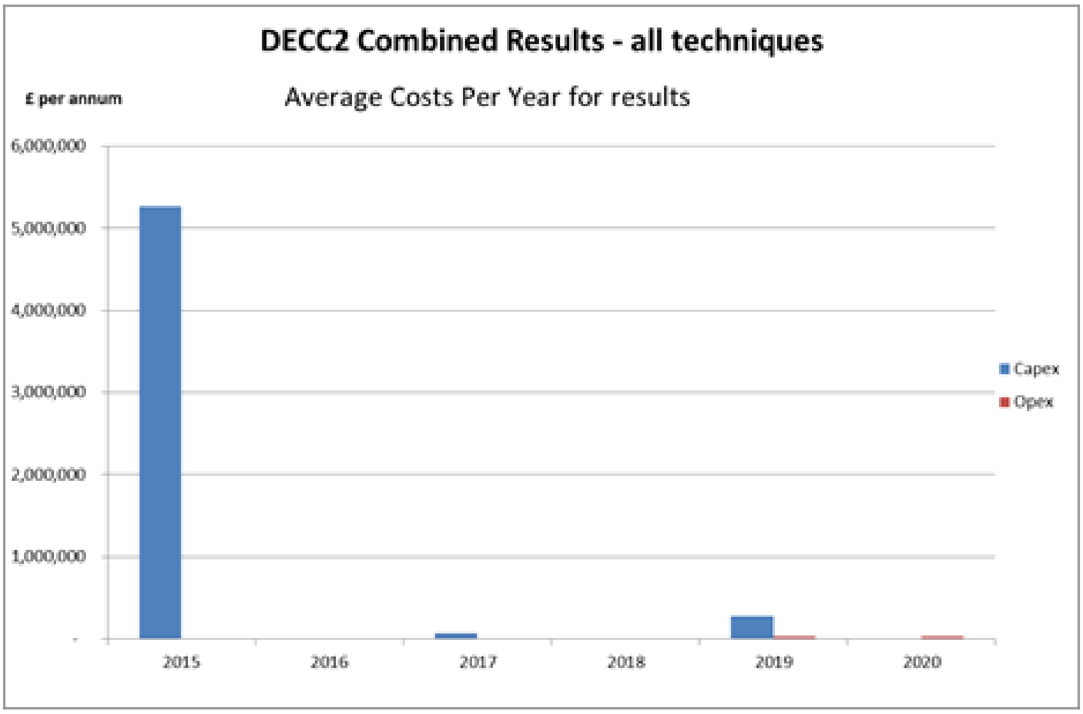
Source: FALCON Project

A.1.4 DECC2 Scenario Investigation

This is a slightly different selection of primaries from that of the DECC1 scenario set as it includes Child's way but not Marlborough Street. However a similar picture of investment and metric costs appears.

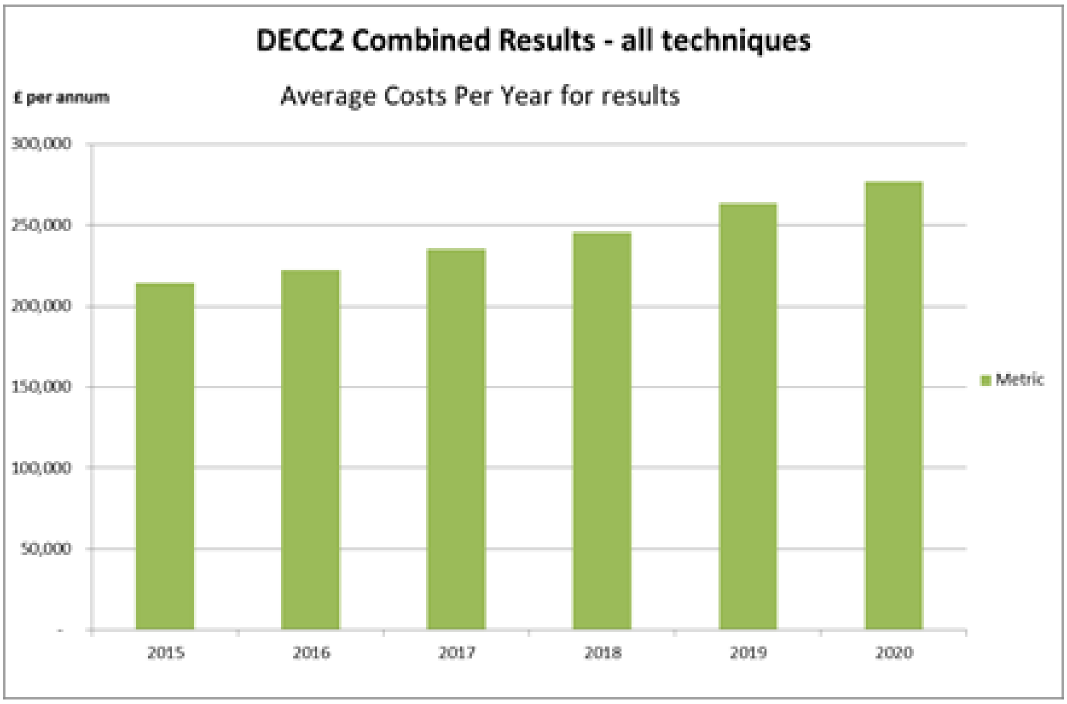
EXP ID	Primary	Year	Scenario	Techniques	Results	NS
4	Fox Milne	2020	DECC2	Smart & Traditional	67	206
6	Newport Pagnell	2020	DECC2	Smart & Traditional	24	481
7	Secklow Gate	2020	DECC2	Smart & Traditional	1	1
8	Bletchley	2020	DECC2	Smart & Traditional	6	
14	Marlborough Street	2020	DECC2	Smart & Traditional	4	
17	Childs Way	2020	DECC2	Smart & Traditional	81	

Figure 71: SIM RUN to 2020 DECC2 - Combined Results all Technique



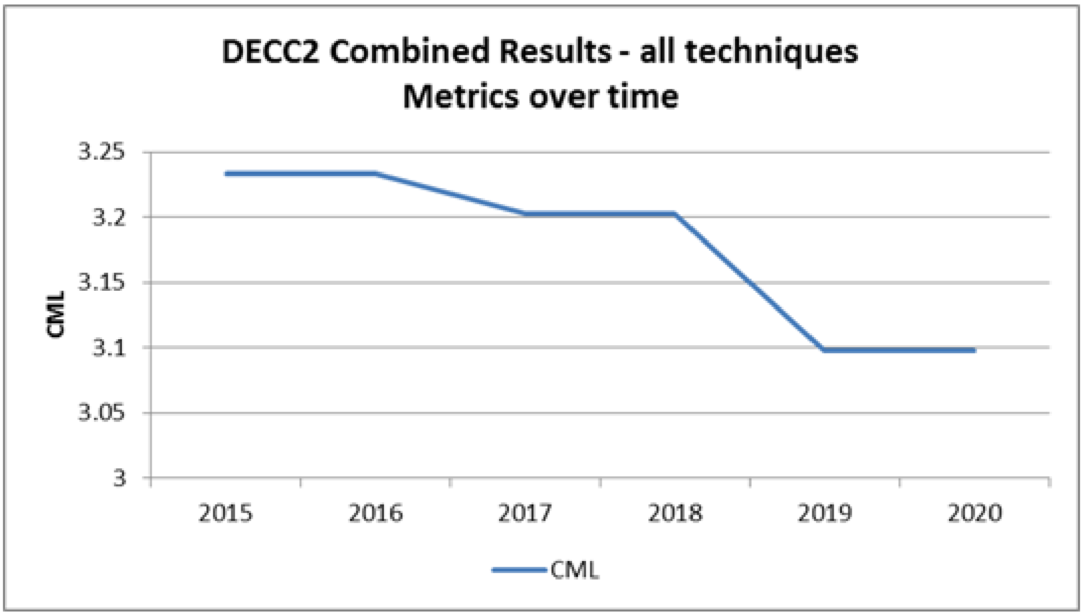
Source: FALCON Project

Figure 72: SIM RUN to 2020 DECC2 - Combined Results all Techniques



Source: FALCON Project

Figure 73: SIM RUN to 2020 DECC2 - Combined Results all Techniques - Combined Metrics



Source: FALCON Project

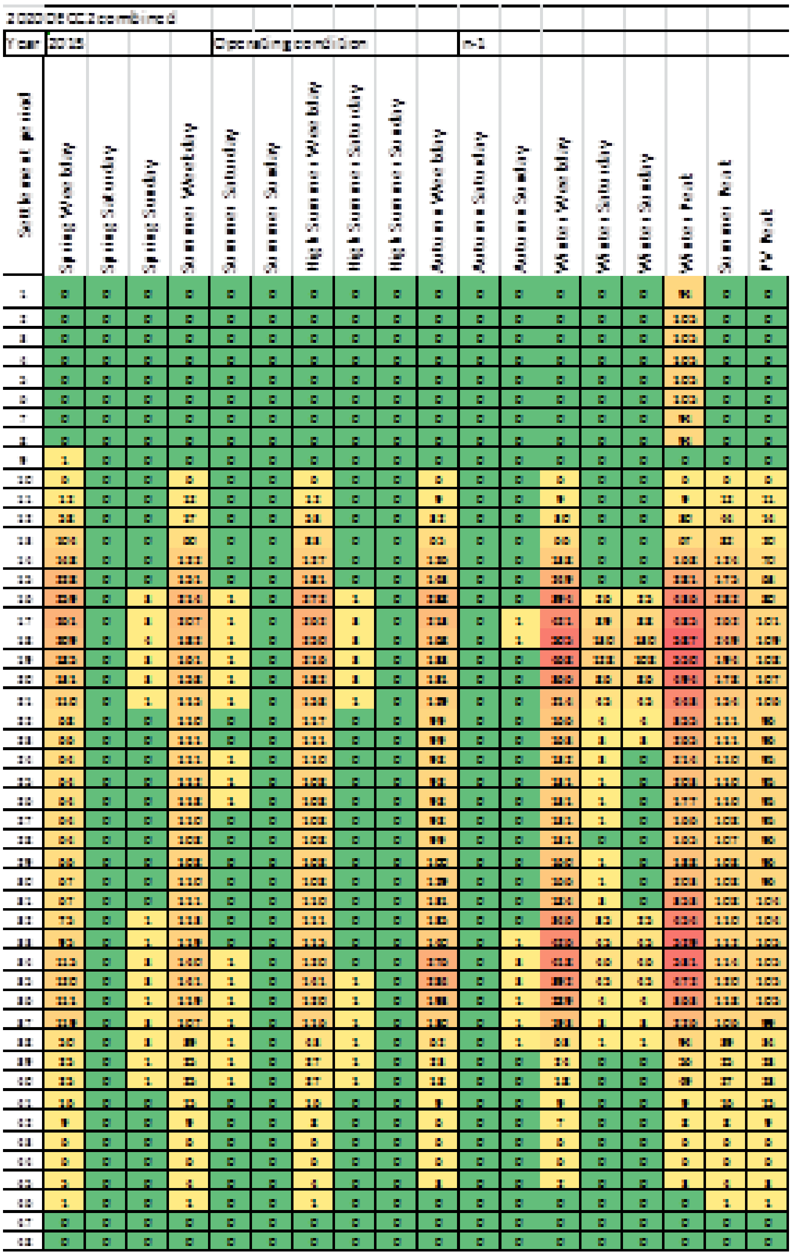
In this case the interventions in 2017 and 2019 have a clear reduction in CML. The split of installations and investments is similar to DECC1, as is the pattern of when network issues arise in 2015 and in other years through to 2020.

2020 DECC1 combined			
		Proportion of	
Technique Name	Number	Installations	CAPEX
DAR(Cable)	11	12%	1%
DAR (Transformer)	12	0%	0%
ALT	21	0%	0%
Mesh	31	3%	1%
Batteries	41	0%	0%
DSM	51	0%	0%
DG	61	0%	0%
Transformer replacement	71	9%	3%
Cable / line upgrade	72	74%	92%
Transfer load to adjacent feeder	73	2%	1%
New feeder	74	0%	3%

A.1.5 Timing of Issues

The pattern of issues in 2015 is similar to that seen for DECC1. As load profiles are very similar for 2015 then differences are more likely to reflect the different Primaries included in the analysis.

Figure 74: Timing of Issues - 2015 (First year)



Source: FALCON Project

The issues arising in the time period 2016-2020 includes a wider range of day types than was seen for DECC1, but it is not clear whether this is due to the load scenarios diverging or the different selection of Primaries within the analysis.

Figure 75: Timing of Issues - 2016 - 2027

2020 DECC2 combined																		
Year	2016 to 2027				Operating condition					n-1								
Settlement period	Spring Weekday	Spring Saturday	Spring Sunday	Summer Weekday	Summer Saturday	Summer Sunday	High Summer Weekday	High Summer Saturday	High Summer Sunday	Autumn Weekday	Autumn Saturday	Autumn Sunday	Winter Weekday	Winter Saturday	Winter Sunday	Winter Peak	Summer Peak	PV Peak
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	16.9	0	0	3.95	0	0	7.9	0	0	0	0	0	0	0	0	0	3.95	0
15	19.8	0	0	7.9	0	0	11.9	0	0	0	0	0	0	0	0	0	11.9	0
16	21.6	0	0	11.9	0	0	11.9	0	0	0	0	0	0	0	0	1	11.9	0
17	17.9	0	0	3.95	0	0	11.9	0	0	0	0	0	0	0	0	2	11.9	0
18	11.9	0	0	3.95	0	0	3.95	0	0	0	0	0	0	0	0	23	3.95	0
19	3.95	0	0	0	0	0	3.95	0	0	0	0	0	0	0	0	5	3.95	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33	3.95	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
34	3.95	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0
35	15.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	0	0
36	11.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
37	11.9	0	0	3.95	0	0	3.95	0	0	0	0	0	0	0	0	1	3.95	0
38	11.9	0	0	3.95	0	0	7.9	0	0	0	0	0	0	0	0	0	3.95	0
39	13.9	0	0	3.95	0	0	3.95	0	0	0	0	0	0	0	0	0	3.95	0
40	13.9	0	0	3.95	0	0	3.95	0	0	0	0	0	0	0	0	0	3.95	0
41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

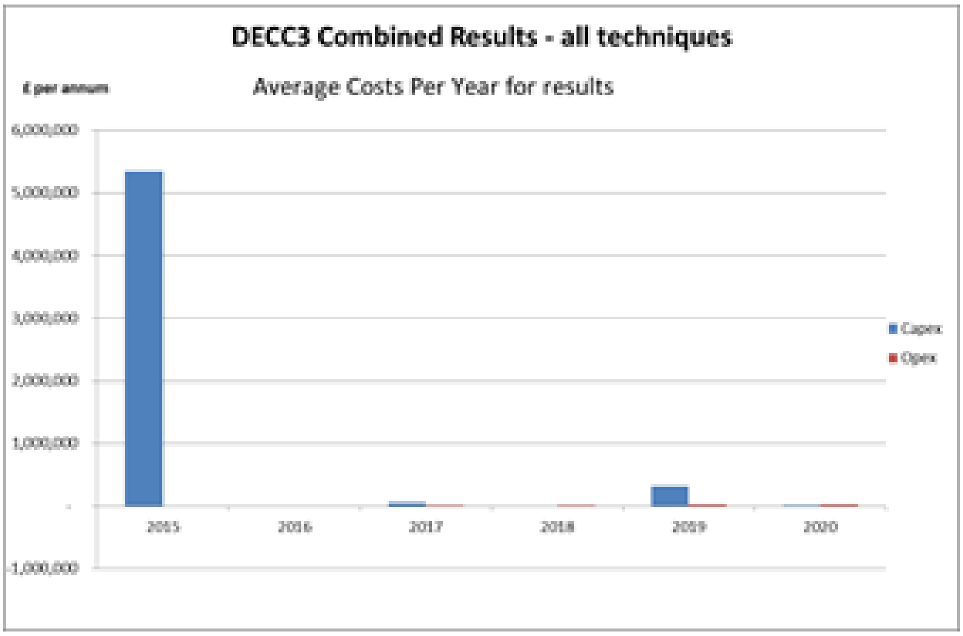
Source: FALCON Project

A.1.6 DECC3 Scenario Investigation

Of the four main DECC load scenarios, DECC3 is the most onerous.
A similar pattern of results is obtained as for the other scenarios with most issues arising in 2015, traditional reinforcement being the predominant solution and CMLs reducing over time.

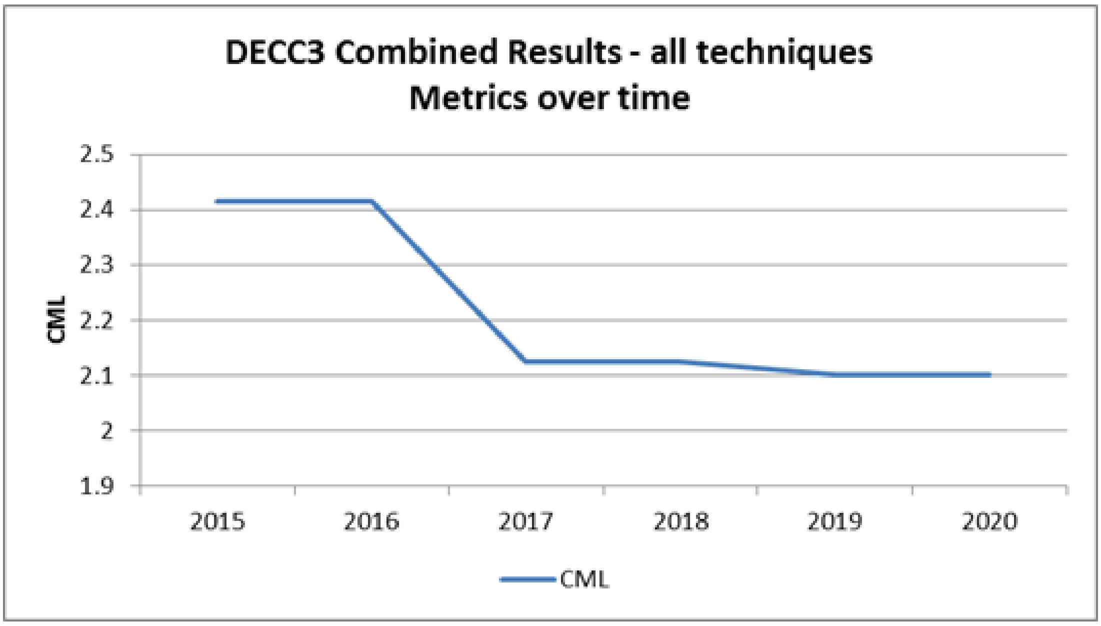
Machine	EXP ID	Primary	Year	DECC	techniques	results	NS
sim3	16	Childs Way	2020	DECC3	Smart & Traditional	1366	3507
sim3	15	Bletchley	2020	DECC3	Smart & Traditional	52	749
sim3	6	Newport Pagnell	2020	DECC3	smart & Traditional	16	356
sim3	4	Fox Milne	2020	DECC3	smart & Traditional	109	304

Figure 76: SIM RUN to 2020 DECC3 - Combined Results all Techniques



Source: FALCON Project

Figure 77: DECC3 Combined Results - Metrics Over Time



Source: FALCON Project

DECC3 Combined Results - all techniques			
		Proportion of	
Technique Name	Number	Installations	CAPEX
DAR(Cable)	11	16%	2%
DAR (Transformer)	12	0%	0%
ALT	21	0%	0%
Mesh	31	2%	1%
Batteries	41	0%	0%
DSM	51	0%	0%
DG	61	0%	0%
Transformer replacement	71	7%	3%
Cable / line upgrade	72	73%	94%
Transfer load to adjacent feeder	73	2%	0%
New feeder	74	0%	0%

A.1.7 Timing of Issues

Figure 78: Timing Of Network Issues 2015 (First Year)

2020 DECC3 combined																		
Year	2015				Operating condition					n-1								
Settlement period	Spring Weekday	Spring Saturday	Spring Sunday	Summer Weekday	Summer Saturday	Summer Sunday	High Summer Weekday	High Summer Saturday	High Summer Sunday	Autumn Weekday	Autumn Saturday	Autumn Sunday	Winter Weekday	Winter Saturday	Winter Sunday	Winter Peak	Summer Peak	PV Peak
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	22	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	33	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	33	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	33	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	33	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	33	0	0
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	22	0	0
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	22	0	0
36	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
40	6	0	0	6	0	0	6	0	0	6	0	0	6	0	0	6	6	6
44	10	0	0	10	0	0	10	0	0	9	0	0	9	0	0	9	10	9
48	38	0	0	10	0	0	33	0	0	20	0	0	20	0	0	20	24	10
52	72	0	0	37	0	0	61	0	0	35	0	0	36	0	0	37	60	10
56	113	0	0	89	0	0	93	0	0	94	0	0	105	0	0	125	90	48
60	151	0	0	93	0	0	119	0	0	106	0	0	138	0	0	160	118	38
64	159	0	3	133	1	0	145	1	0	148	0	0	184	8	7	206	145	54
68	147	0	3	134	1	0	141	3	0	129	0	1	190	16	16	217	141	57
72	88	0	3	116	1	0	138	3	0	93	0	1	202	22	22	236	137	58
76	81	0	3	94	1	0	129	3	0	70	0	0	190	20	18	226	129	58
80	66	0	1	93	1	0	115	3	0	69	0	0	164	14	12	200	113	56
84	45	0	1	62	0	0	90	1	0	69	0	0	138	9	9	184	89	56
88	15	0	0	58	0	0	64	0	0	57	0	0	91	4	4	162	58	54
92	14	0	0	58	0	0	58	0	0	57	0	0	89	3	3	152	58	53
96	14	0	0	58	0	0	58	0	0	56	0	0	70	1	1	138	58	53
100	14	0	0	59	1	0	58	0	0	56	0	0	69	1	1	127	58	53
104	14	0	0	65	1	0	57	0	0	55	0	0	69	1	0	102	58	53
108	14	0	0	58	0	0	57	0	0	56	0	0	69	0	0	91	58	53
112	14	0	0	58	0	0	57	0	0	57	0	0	69	0	0	90	57	53
116	14	0	0	58	0	0	58	0	0	57	0	0	85	0	0	112	57	54
120	14	0	0	58	0	0	58	0	0	69	0	0	91	1	1	128	58	54
124	14	0	0	58	0	0	58	0	0	69	0	0	108	3	3	160	58	54
128	20	0	0	59	0	0	58	0	0	71	0	0	145	7	5	180	58	54
132	22	0	1	62	0	0	60	0	0	75	0	1	152	9	9	206	58	54
136	24	0	3	67	1	0	65	0	0	93	0	3	144	10	9	209	60	55
140	19	0	3	67	1	0	68	1	0	93	0	3	119	9	9	159	62	55
144	19	0	1	64	0	0	65	0	0	83	0	1	97	4	4	126	63	54
148	20	0	3	62	1	0	62	1	0	76	0	1	85	3	3	107	62	57
152	18	0	3	29	1	0	30	1	0	41	0	1	43	1	1	64	29	24
156	15	0	1	15	1	0	16	1	0	13	0	0	15	0	0	36	15	12
160	15	0	1	16	0	0	17	1	0	12	0	0	12	0	0	33	17	13
164	12	0	0	13	0	0	13	0	0	9	0	0	9	0	0	9	13	13
168	9	0	0	9	0	0	8	0	0	6	0	0	7	0	0	8	8	9
172	6	0	0	6	0	0	6	0	0	6	0	0	6	0	0	6	6	6
176	6	0	0	6	0	0	6	0	0	6	0	0	6	0	0	6	6	6
180	5	0	0	4	0	0	4	0	0	3	0	0	2	0	0	3	4	3
184	1	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	1	1
188	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
192	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

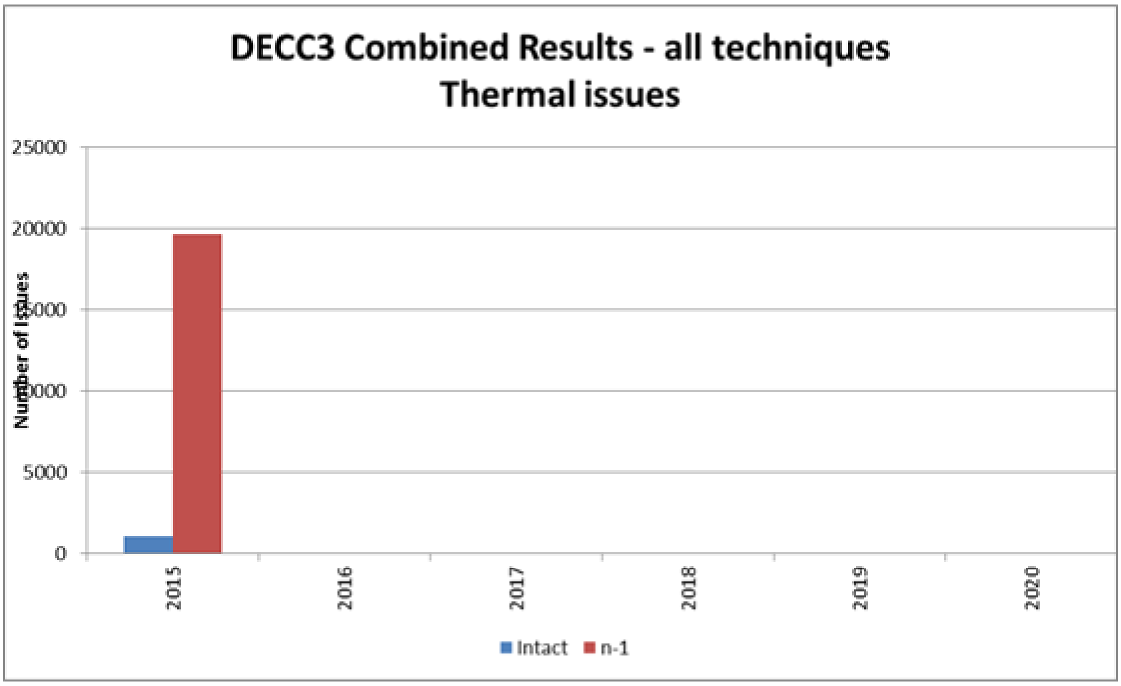
Source: FALCON Project

Figure 79: Timing Of Network Issues 2016 - 2027

2020 DECC3 combined																	
Year	2016 to 2027			Operating condition						n-1							
Settlement period	Spring Weekday	Spring Saturday	Spring Sunday	Summer Weekday	Summer Saturday	Summer Sunday	High Summer Weekday	High Summer Saturday	High Summer Sunday	Autumn Weekday	Autumn Saturday	Autumn Sunday	Winter Weekday	Winter Saturday	Winter Sunday	Winter Peak	Summer Peak	PV Peak
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
52	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
56	5.95	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
60	3.97	0	0	0	0	0	1.95	0	0	0	0	0	0	0	0	0	0.98	0
64	4.98	0	0	0.98	0	0	1.95	0	0	0	0	0	0	0	0	0	1.95	0
68	1.95	0	0	0	0	0	0.98	0	0	0	0	0	0	0	0	3	0.98	0
72	0.98	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0
76	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0
80	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
84	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
88	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
92	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
96	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
104	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
108	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
112	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
116	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
120	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
124	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
128	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
132	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
136	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.98	0	0
140	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0
144	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
148	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
152	0.98	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
156	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
160	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
164	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
168	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
172	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
176	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
180	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
184	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
188	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
192	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

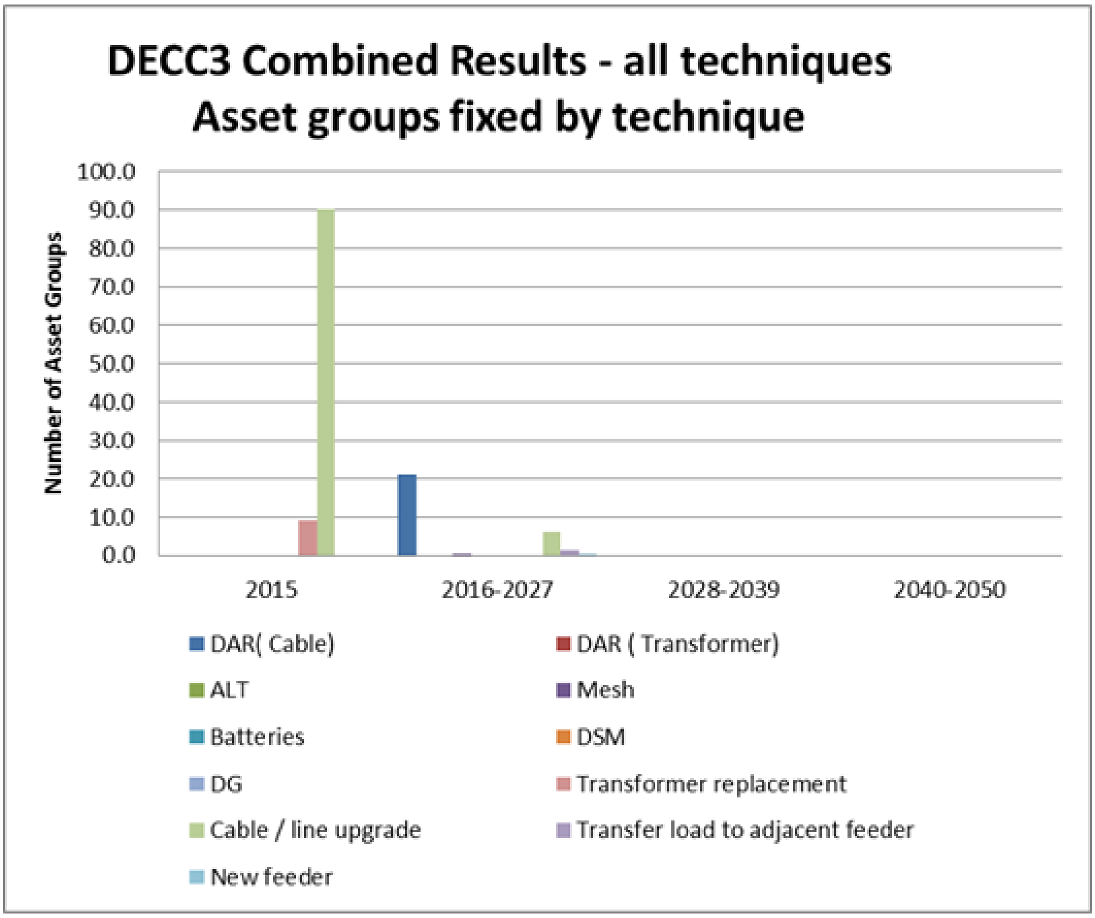
Source: FALCON Project

Figure 80: DECC3 Combined Results - Thermal Issues



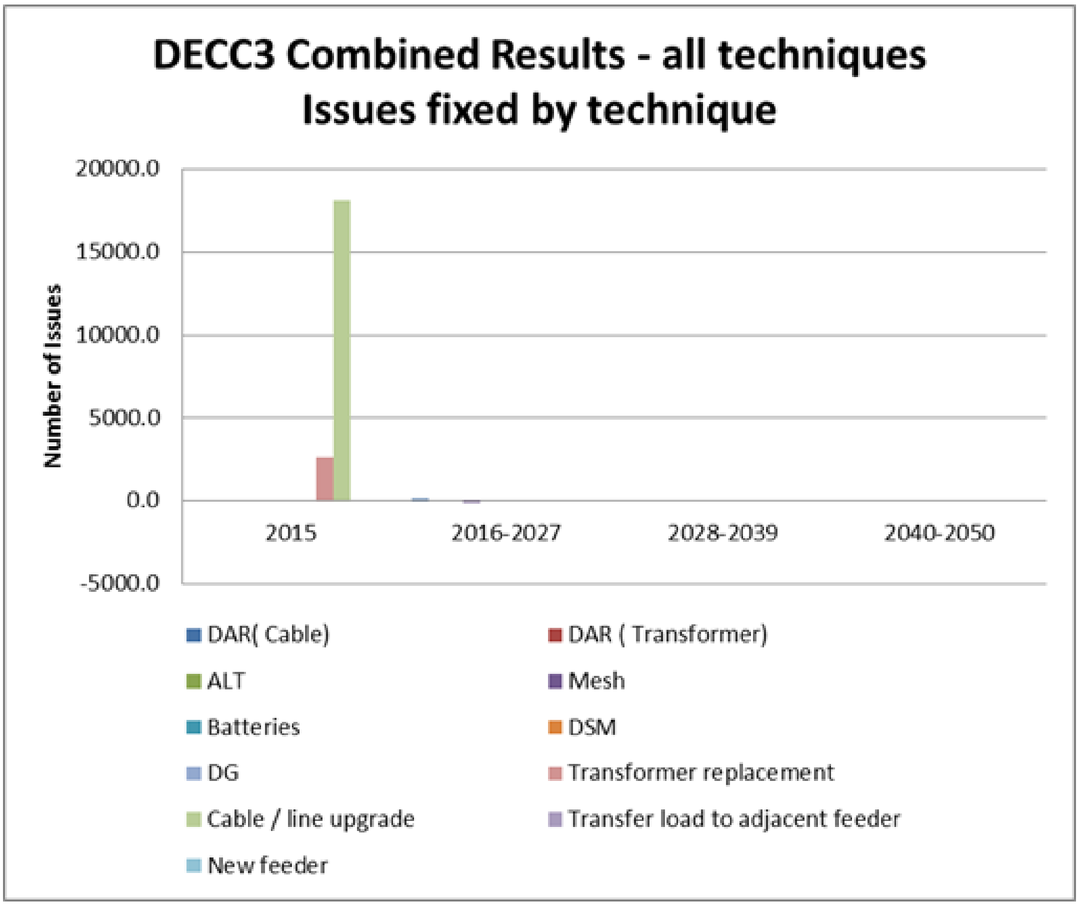
Source: FALCON Project

Figure 81: DECC3 Combined Results - Asset Groups Fixed by Techniques



Source: FALCON Project

Figure 82: DECC3 Combined Results - Issues Fixed by Techniques



Source: FALCON Project

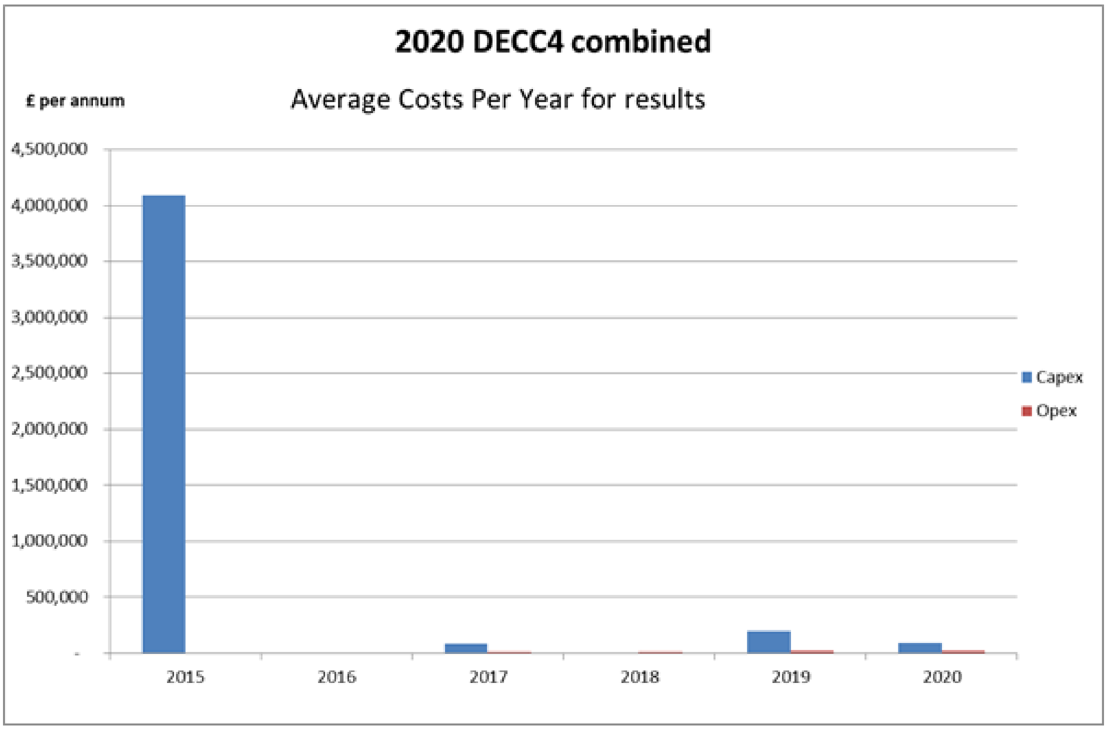
A.1.8 DECC4 Scenario Investigation

The DECC4 Runs were as follows:

Host	EXP ID	Primary	Year	DECC	techniques	results	NS
sim4	4	Fox Milne	2020	DECC4	Smart & Traditional	112	287
sim4	10	Childs Way	2020	DECC4	smart & Traditional	91	1564
sim4	20	Bletchley	2020	DECC4	smart & Traditional	25	549
sim4	21	Marlborough St	2020	DECC4	smart & Traditional	51	415

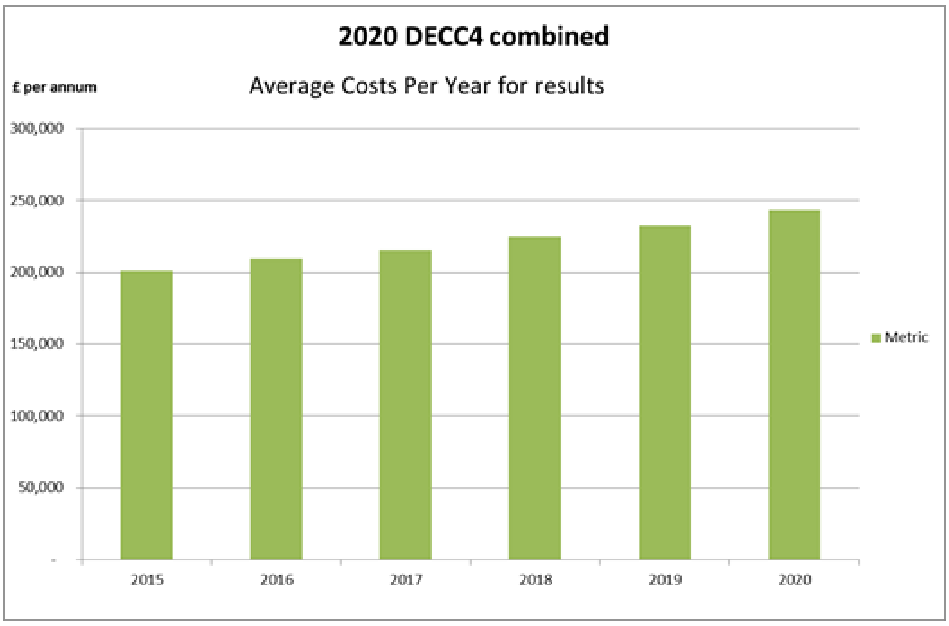
Once again the results are similar to the other Scenarios, but with exception of the pattern of issues identified in the period 2016-2020. In this case the newly found issues are spread across a wider number of day types rather than being concentrated within Winter Peak or Spring Weekday.

Figure 83: SIM RUN to 2020 DECC4 - Combined Results all Technique



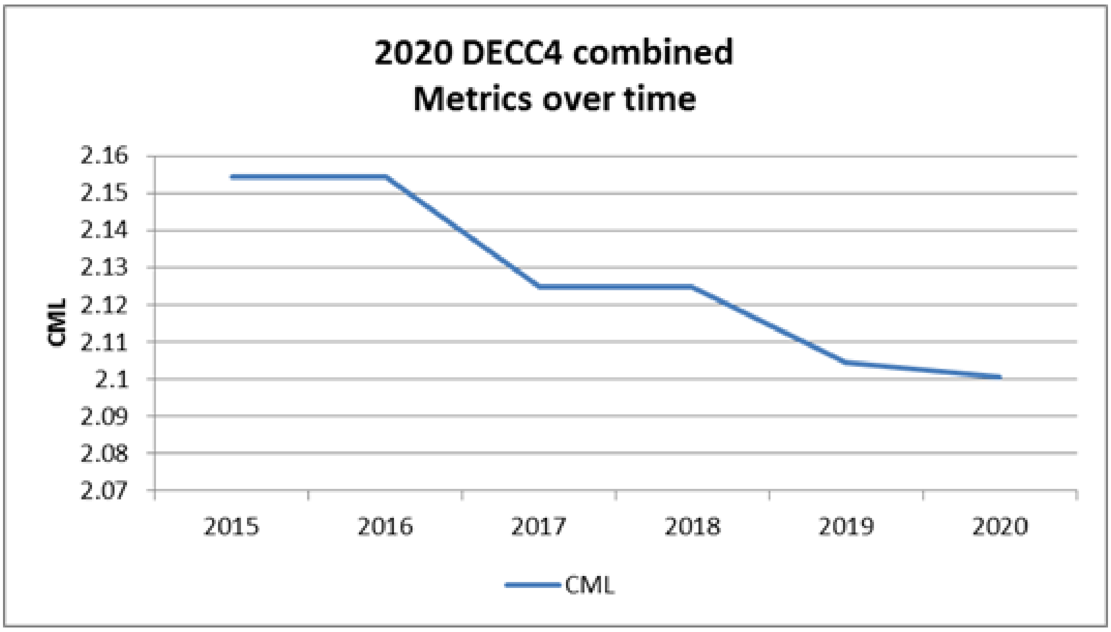
Source: FALCON Project

Figure 84: SIM RUN to 2020 DECC4 - Combined Results all Techniques



Source: FALCON Project

Figure 85: DECC4 Combined Results - Metrics Over Time



Source: FALCON Project

2020 DECC4 combined			
		Proportion of	
Technique Name	Number	Installations	CAPEX
DAR(Cable)	11	14%	1%
DAR (Transformer)	12	0%	0%
ALT	21	0%	0%
Mesh	31	3%	1%
Batteries	41	0%	0%
DSM	51	0%	0%
DG	61	0%	0%
Transformer replacement	71	9%	3%
Cable / line upgrade	72	70%	91%
Transfer load to adjacent feeder	73	4%	1%
New feeder	74	0%	2%

A.1.9 Timing of Issues

Figure 86: Timing Of Network Issues 2015 (First Year)

2020 DECC4 combined																		
Year	2015				Operating condition					n-1								
Settlement period	Spring Weekday	Spring Saturday	Spring Sunday	Summer Weekday	Summer Saturday	Summer Sunday	High Summer Weekday	High Summer Saturday	High Summer Sunday	Autumn Weekday	Autumn Saturday	Autumn Sunday	Winter Weekday	Winter Saturday	Winter Sunday	Winter Peak	Summer Peak	PV Peak
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	22	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	22	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	22	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	22	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	22	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	22	0	0
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	22	0	0
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	22	0	0
36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
44	2	0	0	2	0	0	2	0	0	0	0	0	0	0	0	0	2	2
48	20	0	0	8	0	0	20	0	0	12	0	0	10	0	0	10	20	4
52	32	0	0	22	0	0	22	0	0	30	0	0	30	0	0	30	22	10
56	44	0	0	50	0	0	52	0	0	56	0	0	68	0	0	87	51	35
60	70	0	0	60	0	0	88	0	0	73	0	0	105	0	0	124	81	39
64	81	0	3	123	1	0	130	2	0	140	0	0	161	7	6	182	130	69
68	92	0	4	115	1	0	143	3	0	122	0	1	177	14	14	202	141	88
72	91	2	4	124	3	0	139	3	0	129	0	1	189	19	19	220	139	96
76	75	0	3	121	1	0	125	3	0	108	0	0	181	19	19	213	125	94
80	71	0	3	119	1	0	122	3	0	106	0	0	168	15	14	187	122	94
84	71	0	1	100	1	0	119	1	0	104	0	0	140	9	9	177	118	94
88	54	0	0	97	0	0	103	1	0	86	0	0	127	4	4	164	97	86
92	52	0	0	97	0	0	97	0	0	86	0	0	126	3	3	155	97	86
96	50	0	0	97	1	0	96	0	0	86	0	0	107	3	3	140	97	86
100	50	0	0	98	1	0	94	0	0	86	0	0	106	3	1	130	96	86
104	50	0	0	103	1	0	94	0	0	86	0	0	106	1	1	127	96	86
108	51	0	0	96	0	0	94	0	0	86	0	0	106	1	1	127	94	86
112	52	0	0	94	0	0	94	0	0	86	0	0	106	0	0	127	94	86
116	52	0	0	96	0	0	94	0	0	86	0	0	124	1	0	128	94	86
120	53	0	0	96	0	0	94	0	0	106	0	0	128	1	0	131	94	86
124	54	0	0	97	0	0	97	0	0	106	0	0	131	3	0	162	94	94
128	61	0	1	99	0	0	98	0	0	110	0	0	147	8	3	180	96	94
132	63	0	1	105	1	0	101	0	0	117	0	1	161	9	4	207	99	94
136	66	0	3	109	1	0	106	1	0	132	0	3	163	10	4	208	101	94
140	61	0	3	109	1	0	109	1	0	131	0	3	160	9	4	188	106	95
144	59	0	1	105	1	0	106	1	0	121	0	1	133	4	0	160	104	94
148	58	0	3	93	1	0	101	1	0	103	0	1	110	3	0	131	92	87
152	17	0	3	27	1	0	31	1	0	37	0	1	38	1	0	57	27	24
156	10	0	1	13	1	0	13	1	0	11	0	0	11	0	0	30	13	11
160	10	0	1	13	1	0	13	1	0	6	0	0	6	0	0	26	13	11
164	4	0	0	3	0	0	4	0	0	0	0	0	0	0	0	0	4	3
168	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
172	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
176	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
180	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
184	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
188	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
192	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

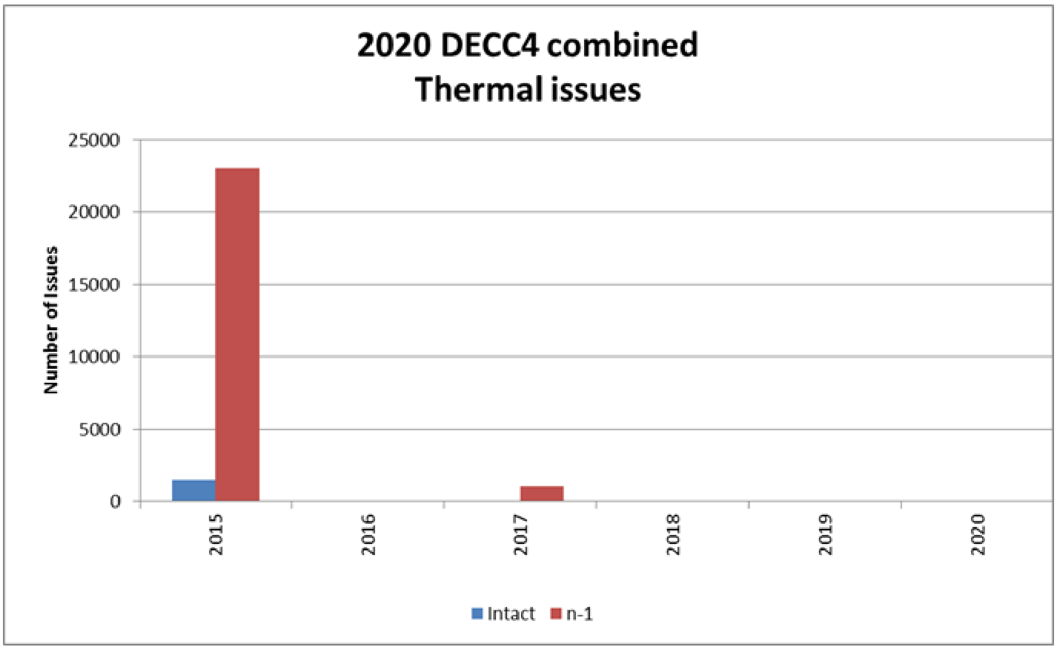
Source: FALCON Project

Figure 87: Timing Of Network Issues 2016 - 2027

2020 DECC4 combined																		
Year	2016 to 2027				Operating condition						n-1							
Settlement period	Spring Weekday	Spring Saturday	Spring Sunday	Summer Weekday	Summer Saturday	Summer Sunday	High Summer Weekday	High Summer Saturday	High Summer Sunday	Autumn Weekday	Autumn Saturday	Autumn Sunday	Winter Weekday	Winter Saturday	Winter Sunday	Winter Peak	Summer Peak	PV Peak
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	2	2	0	2	0	0	2	2	0	0	0	0	0	0	0	0	2	2
52	2	2	2	2	2	2	2	4	2	0	0	0	0	0	0	0	2	2
56	9	2	2	2	2	2	8	10	2	0	0	0	0	0	0	0	8	2
60	9	8	8	8	2	2	8	10	2	0	0	0	0	0	0	0	8	2
64	9	8	8	8	8	2	8	16	8	0	0	0	0	0	0	0	8	2
68	8	8	8	8	2	2	8	16	8	0	0	0	0	0	0	0	8	2
72	8	8	8	8	2	2	8	16	8	0	0	0	0	0	0	7	8	2
76	8	8	8	8	2	2	8	16	8	0	0	0	0	0	0	3	8	2
80	8	8	2	2	2	2	8	16	2	0	0	0	0	0	0	0	8	2
84	2	2	2	2	2	2	2	10	2	0	0	0	0	0	0	0	2	2
88	2	2	2	2	2	2	2	10	2	0	0	0	0	0	0	0	2	2
92	2	0	2	2	2	2	2	10	2	0	0	0	0	0	0	0	2	2
96	2	0	2	2	2	2	2	10	2	0	0	0	0	0	0	0	2	0
100	2	0	2	2	2	2	2	4	2	0	0	0	0	0	0	0	2	0
104	2	0	2	2	2	2	2	4	2	0	0	0	0	0	0	0	2	0
108	2	0	2	2	2	2	2	4	2	0	0	0	0	0	0	0	2	0
112	2	0	2	2	2	2	2	4	2	0	0	0	0	0	0	0	2	0
116	2	0	2	2	2	2	2	4	2	0	0	0	0	0	0	0	2	0
120	2	0	2	2	2	2	2	4	2	0	0	0	0	0	0	0	2	2
124	2	0	2	2	2	2	2	4	2	0	0	0	0	0	0	0	2	2
128	2	0	2	2	2	2	2	4	2	0	0	0	0	0	0	0	2	2
132	2	0	2	2	2	2	2	4	2	0	0	0	0	0	0	0	2	2
136	2	0	2	2	2	2	2	4	2	0	0	0	0	0	0	2	2	2
140	4	0	2	2	2	2	2	4	2	0	0	0	0	0	0	4	2	2
144	2	0	2	2	2	2	2	4	2	0	0	0	0	0	0	0	2	2
148	2	0	2	2	2	2	2	4	2	0	0	0	0	0	0	0	2	2
152	2	0	2	2	2	2	2	4	2	0	0	0	0	0	0	0	2	2
156	2	0	2	2	2	2	2	4	2	0	0	0	0	0	0	0	2	2
160	2	0	2	2	2	2	2	4	2	0	0	0	0	0	0	0	2	2
164	2	0	2	2	2	2	2	4	2	0	0	0	0	0	0	0	2	2
168	2	0	2	2	2	2	2	4	2	0	0	0	0	0	0	0	2	2
172	2	0	0	2	2	2	2	2	0	0	0	0	0	0	0	0	2	2
176	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
180	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
184	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
188	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
192	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

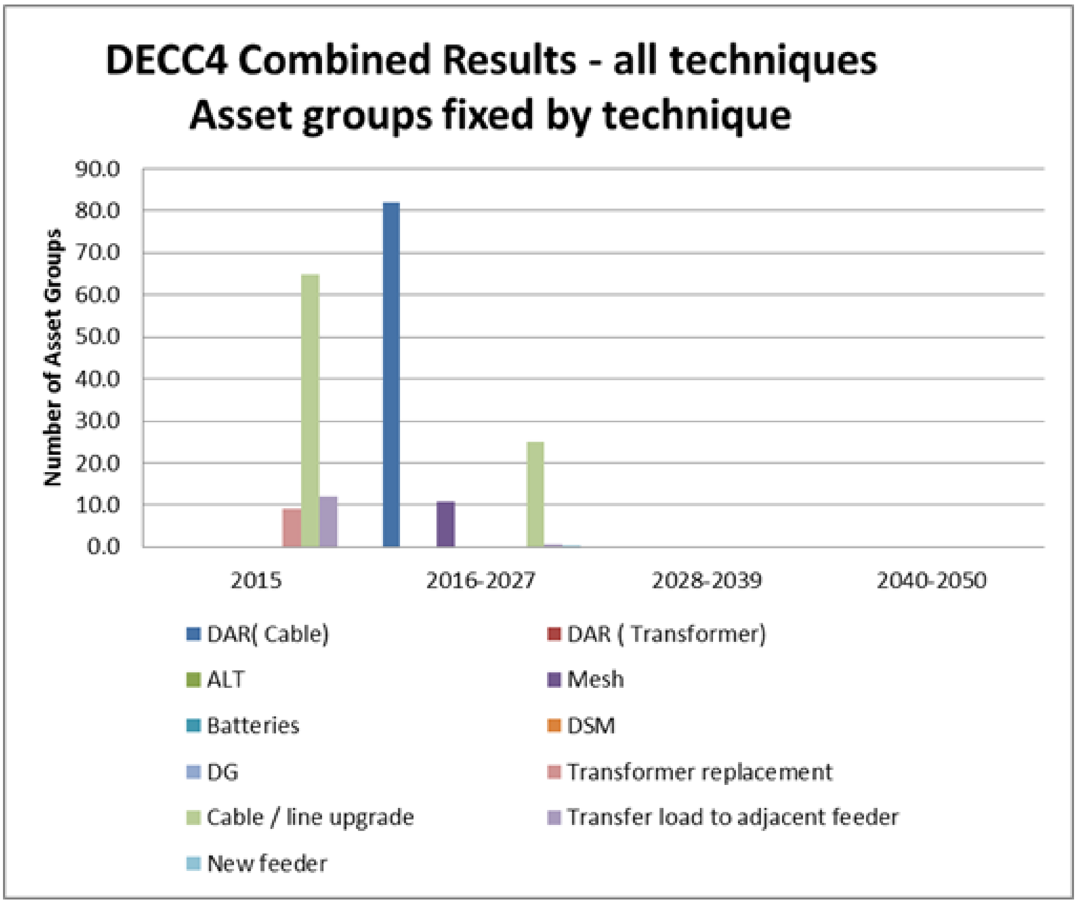
Source: FALCON Project

Figure 88: DECC4 Combined Results - Thermal Issues



Source: FALCON Project

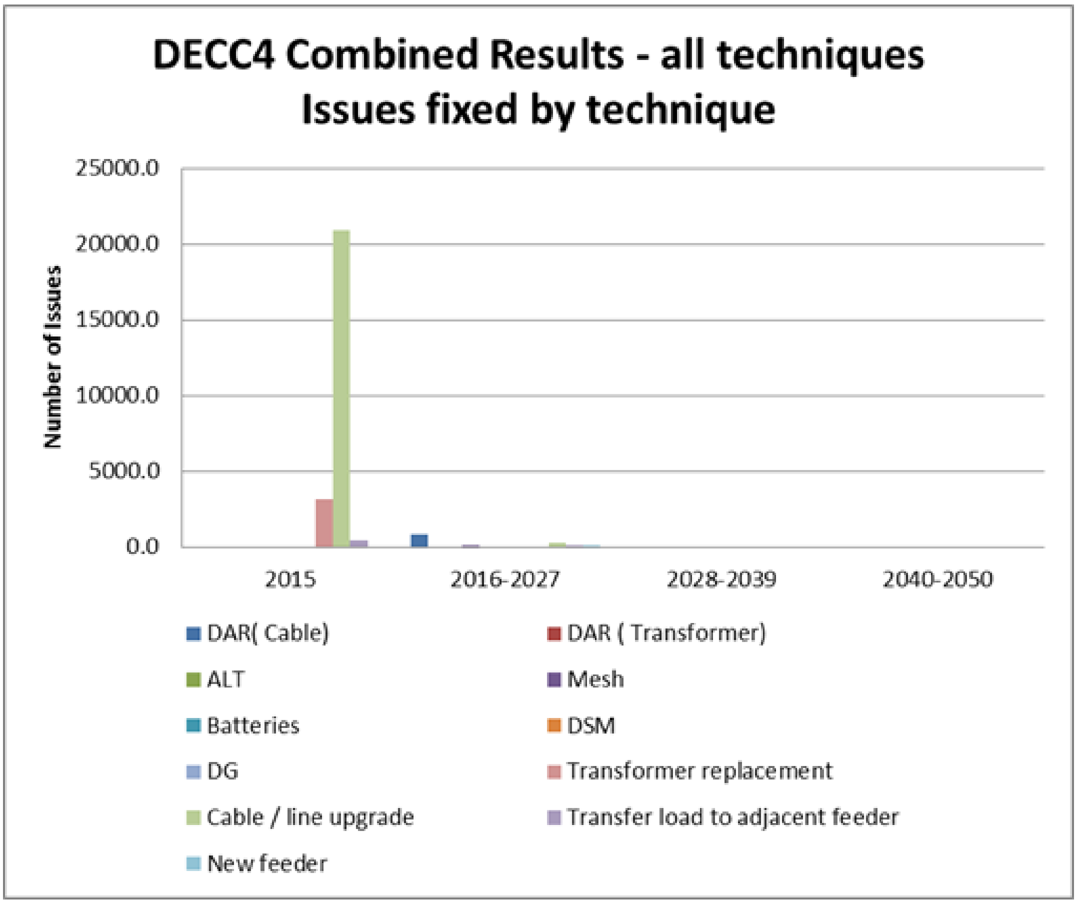
Figure 89: DECC4 Combined Results - Asset Groups Fixed by Technique



Source: FALCON Project

Figure 90: Combined Scenarios to 2020 - Issues Fixed by Technique

Source: FALCON Project



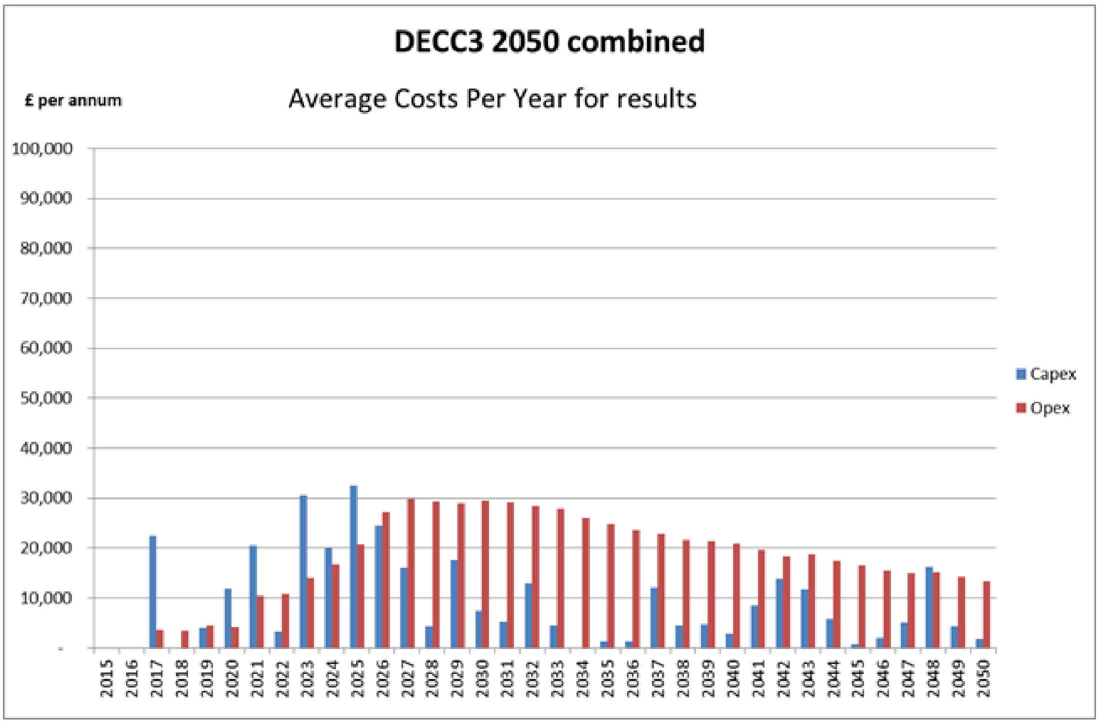
Source: FALCON Project

A.1.10 2050 Scenario Investigation DECC3 –Combined Results

The previous analysis has been based on Runs that stop at 2020. Considering those Runs that extend to 2050 shows an increased uptake in smart techniques.

Host	EXP ID	Primary	Year	DECC	techniques	results	NS
sim3	12	Secklow Gate	2050	DECC3	Smart & Traditional	118	635
sim3	3	Childs Way	2050	DECC3	Smart & Traditional	252	832
sim3	1	Fox Milne	2050	DECC3	Smart & Traditional	52	1004

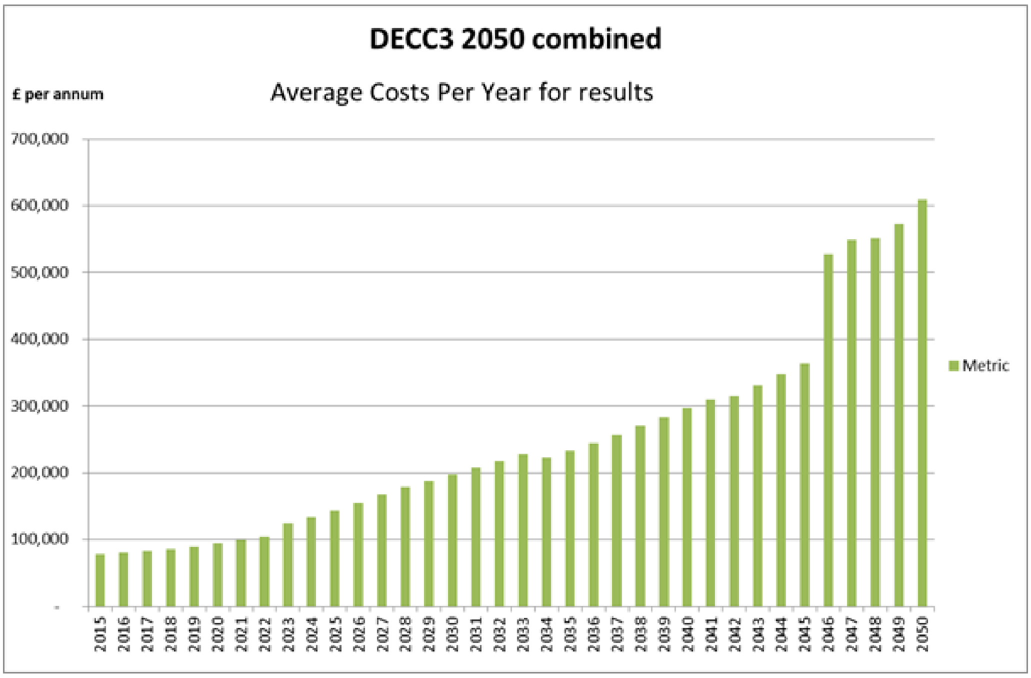
Figure 91: Combined Results for DECC3 to 2050 - Average Costs Per Year



Source: FALCON Project

This chart has 2015 CAPEX expenditure excluded so that the scale of the remaining items can be seen more clearly. The "lumpy" nature of investment can be seen with investment levels fluctuating significantly between years. The operating costs associated with new investments can be seen to increase as new assets are added to the network and become more significant than capital costs.

Figure 92: Combined Results for DECC3 to 2050 - Average Costs Per Year

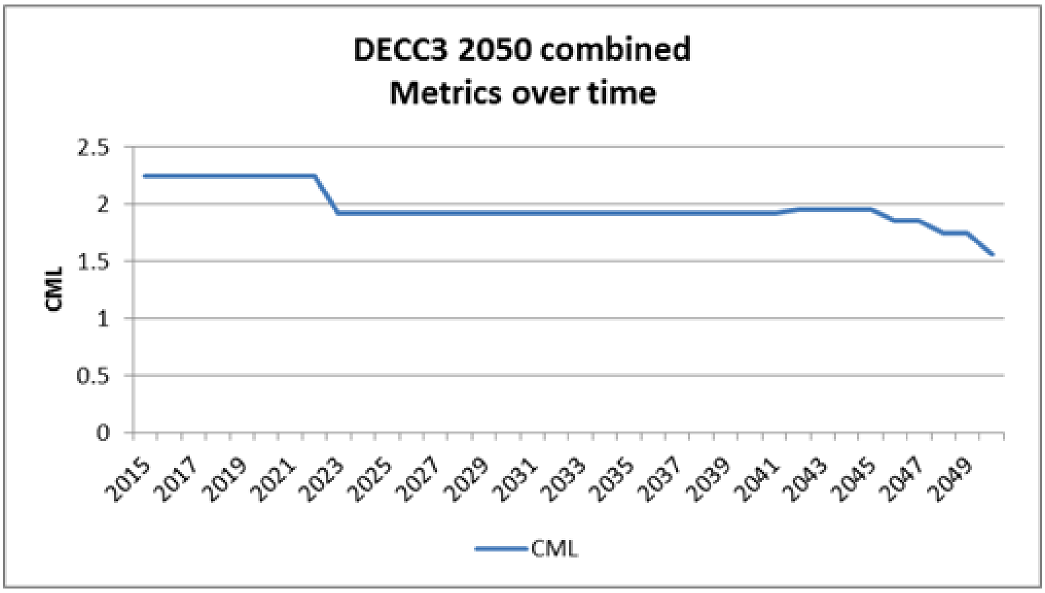


Source: FALCON Project

The chart above shows that the pattern of increasing metric costs extends beyond 2020 and continues to 2050.

The chart shows that the general decline in CMLS continues over the longer time-frame but is not a steady decline.

Figure 93: 2050 DECC3 Scenario - Combined Metrics Over Time



Source: FALCON Project

With longer timeframes, less the smart techniques make up a greater proportion of the number of interventions and also the investment costs.

DECC3 2050 combined			
Technique Name	Number	Proportion of Installations	CAPEX
DAR(Cable)	11	29%	5%
DAR (Transformer)	12	31%	6%
ALT	21	0%	0%
Mesh	31	5%	3%
Batteries	41	0%	0%
DSM	51	0%	0%
DG	61	0%	0%
Transformer replacement	71	10%	10%
Cable / line upgrade	72	23%	75%
Transfer load to adjacent feeder	73	1%	0%
New feeder	74	1%	1%

A.1.11 Timing of Issues

Fewer issues are shown below due to only three primaries being included in this analysis.

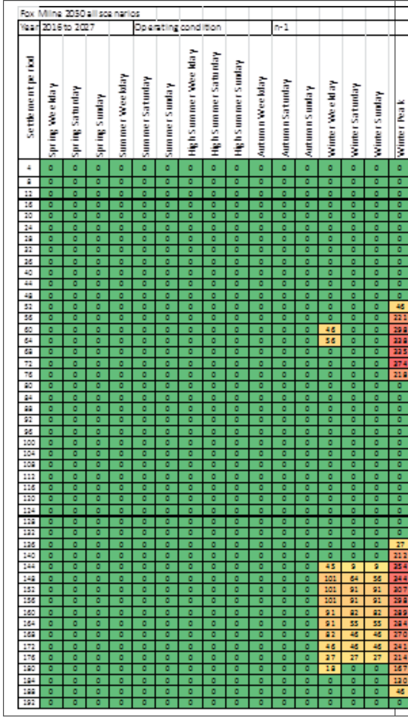
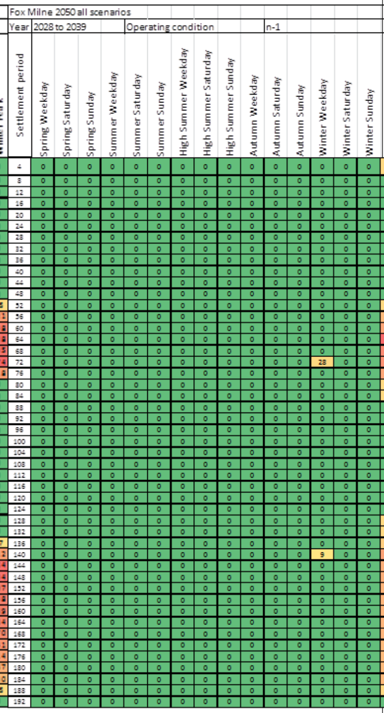
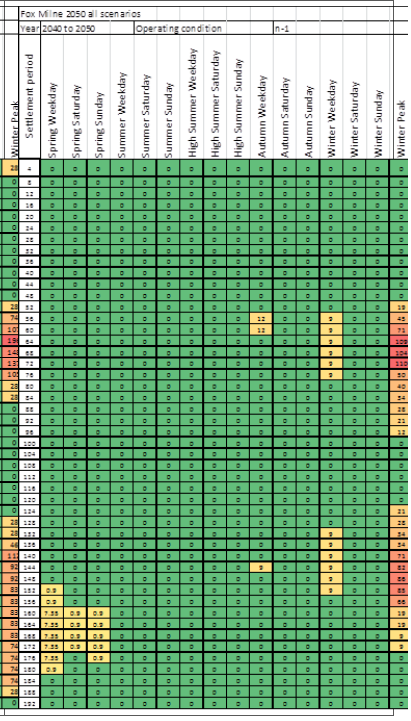
Figure 94: Tining of Issues - Year 1 (2015)

DECC3 2050 combined

Year 2015 | Operating condition n-1

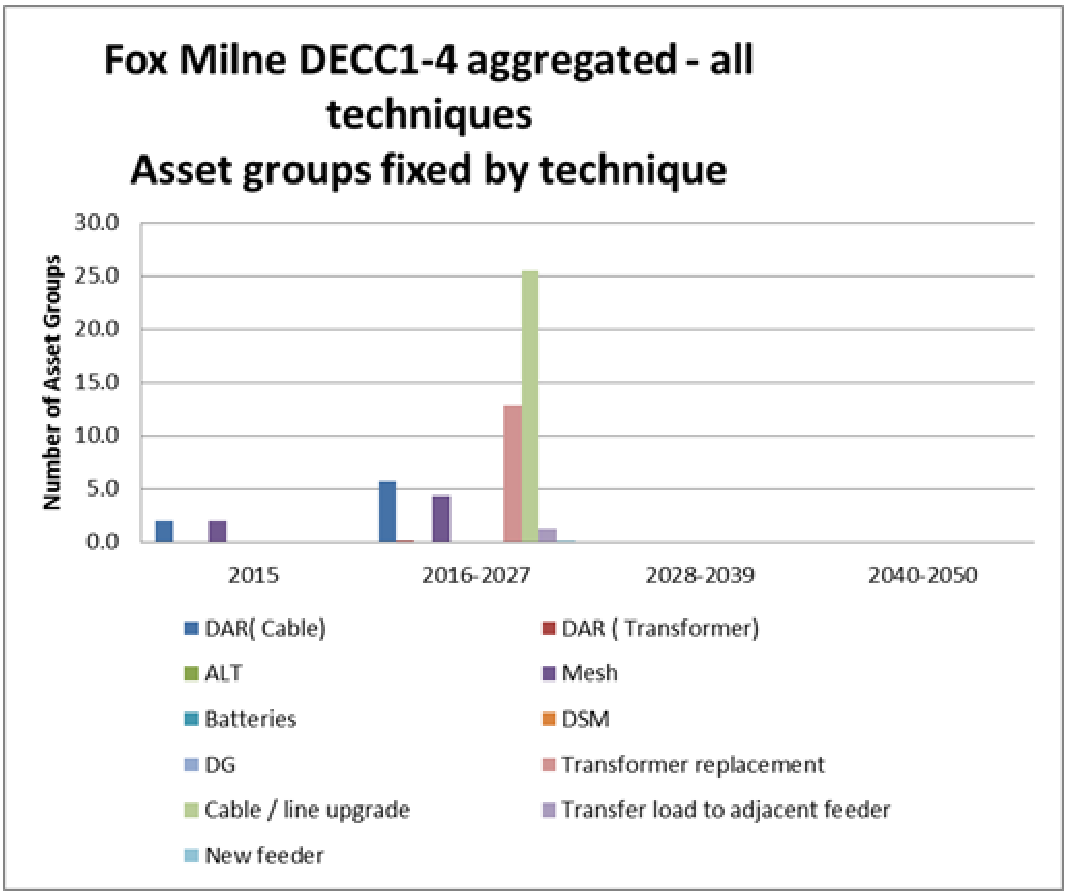
Settlement period	Spring Weekday	Spring Saturday	Spring Sunday	Summer Weekday	Summer Saturday	Summer Sunday	High Summer Weekday	High Summer Saturday	High Summer Sunday	Autumn Weekday	Autumn Saturday	Autumn Sunday	Winter Weekday	Winter Saturday	Winter Sunday	Winter Peak	Summer Peak	PV Peak
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
42	8	0	0	0	0	0	1	0	0	9	0	0	18	0	0	27	0	0
45	13	0	0	1	0	0	8	0	0	18	0	0	32	0	0	41	8	0
48	16	0	0	8	0	0	13	0	0	27	0	0	40	2	2	50	13	0
51	16	0	0	8	0	0	11	0	0	6	0	0	41	8	8	53	11	0
54	11	0	0	6	0	0	10	0	0	6	0	0	49	12	12	62	10	0
57	8	0	0	6	0	0	6	0	0	0	0	0	46	12	10	59	6	0
60	6	0	0	6	0	0	6	0	0	0	0	0	38	8	6	48	6	0
63	6	0	0	3	0	0	6	0	0	0	0	0	15	4	4	42	6	0
66	1	0	0	0	0	0	5	0	0	0	0	0	6	0	0	37	0	0
69	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0	28	0	0
72	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15	0	0
75	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	6	0	0
78	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	6	0	0
81	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0
84	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0
87	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0	6	0	0
90	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0	6	0	0
93	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0	35	0	0
96	6	0	0	0	0	0	0	0	0	0	0	0	20	2	0	46	0	0
99	8	0	0	0	0	0	0	0	0	0	0	0	28	4	4	58	0	0
102	10	0	0	2	0	0	0	0	0	16	0	0	28	4	4	59	0	0
105	5	0	0	2	0	0	2	0	0	14	0	0	28	4	4	40	0	0
108	4	0	0	0	0	0	0	0	0	5	0	0	14	0	0	30	0	0
111	4	0	0	0	0	0	0	0	0	0	0	0	6	0	0	15	0	0
114	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0
117	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0
120	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0
123	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
126	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
129	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
132	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
135	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
138	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
141	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
144	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Source: FALCON Project

Figure 95: Timing of Issues - Fox Milne to 2050 - 2016 - 2027	Figure 96: Timing of Issues - Fox Milne to 2050 - 2028 - 2039	Figure 97: Timing of Issues - Fox Milne to 2050 - 2040 - 2050
		

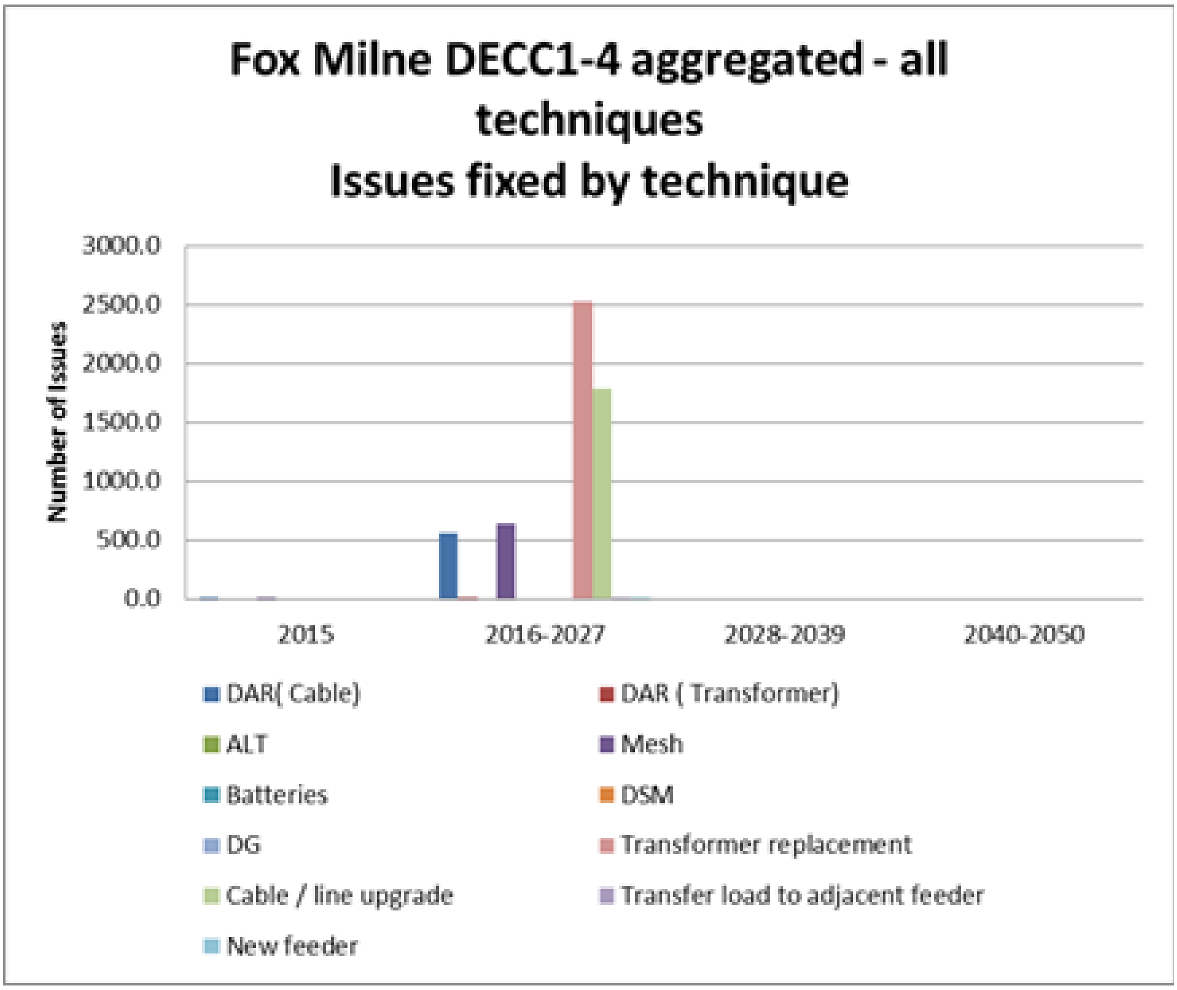
Source: FALCON Project

Figure 98: Fox Milne DECC1-4 - Asset Groups Fixed by Technique



Source: FALCON Project

Figure 99: Fox Milne DECC1-4 - Issues Fixed by Technique

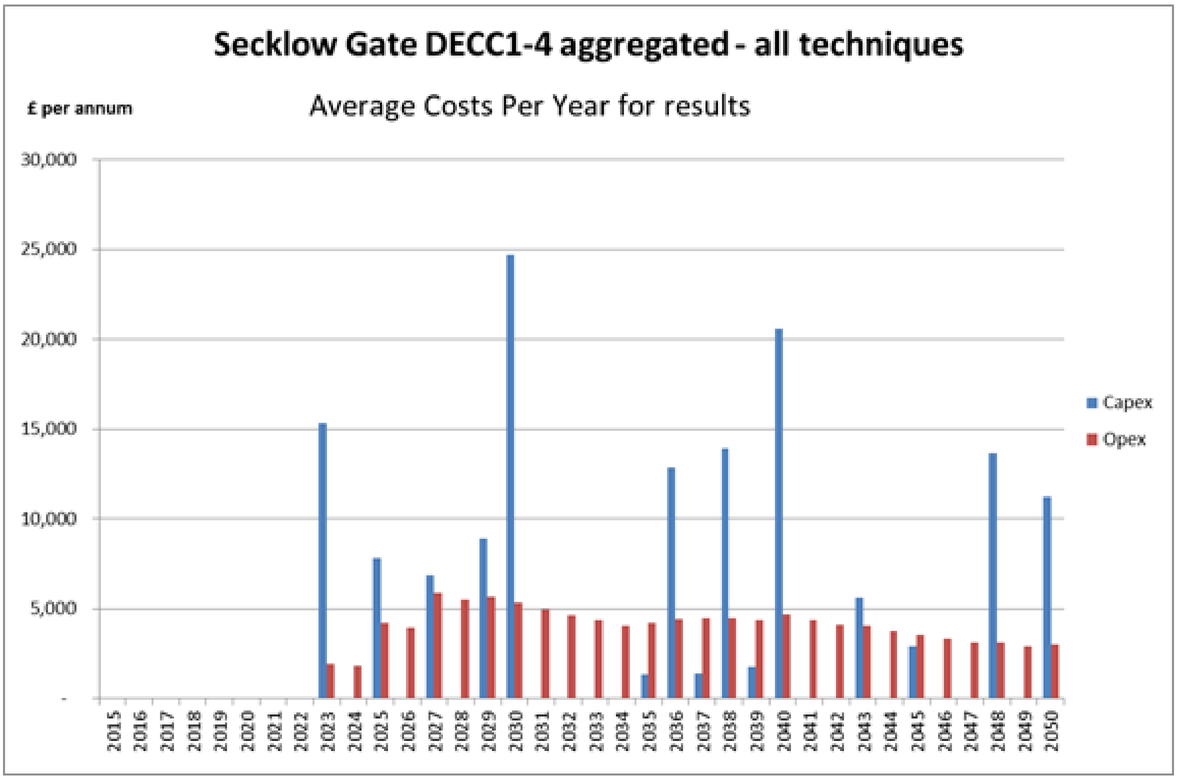


Source: FALCON Project

7.4.1 Secklow Gate – All Scenarios to 2050

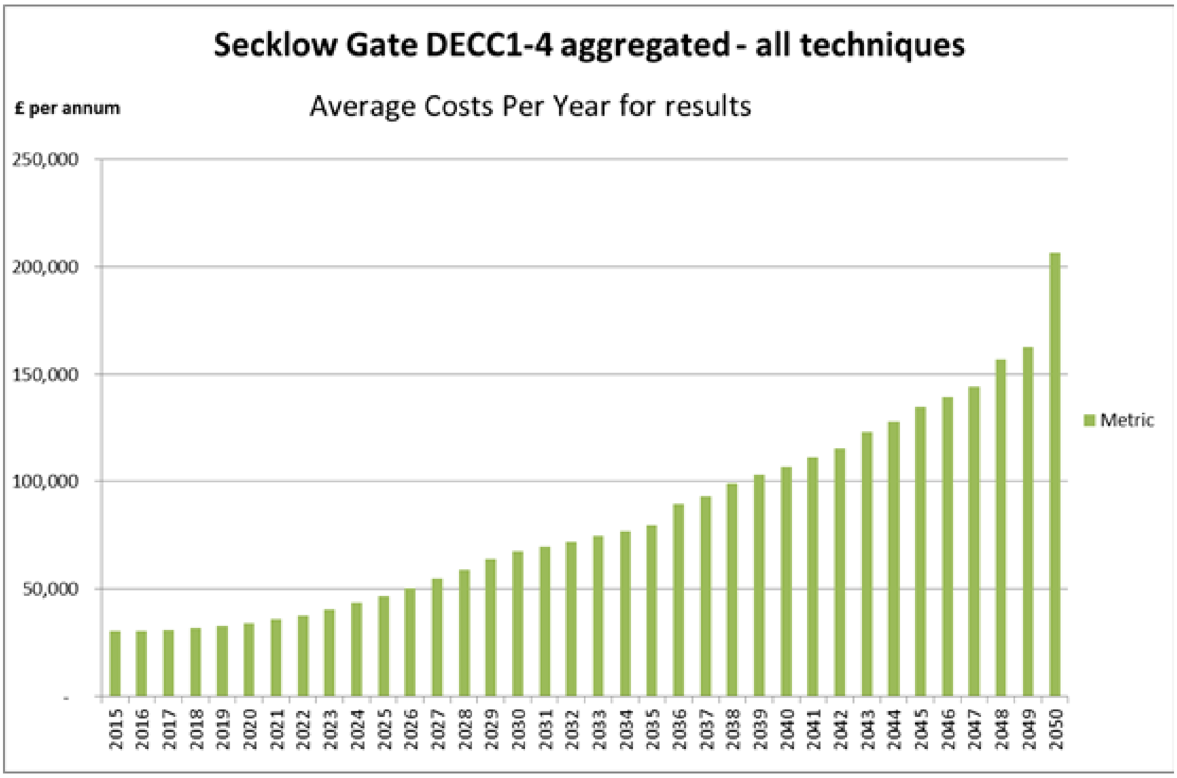
Machine	EXP ID	Primary	Year	DECC	techniques	results	NS
sim2	10	Secklow Gate	2050	DECC2	Smart & Traditional	432	
sim1	19	Secklow Gate	2050	DECC1	Smart & Traditional	273	563
sim3	12	Secklow Gate	2050	DECC3	Smart & Traditional	118	635
sim4	12	Secklow Gate	2050	DECC4	smart & Traditional	7	9

Figure 100: Secklow Gate - DECC1-4 to 2050 Aggregated Costs all Techniques



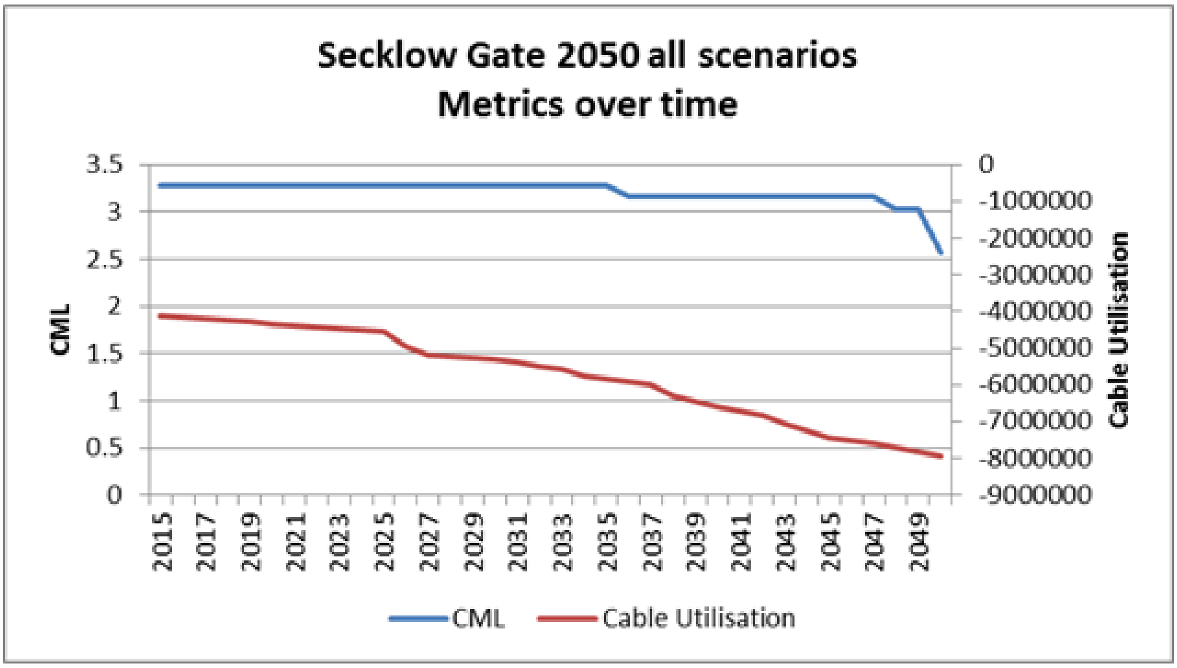
Source: FALCON Project

Figure 101: Secklow Gate DECC1-4 to 2050 - Average Costs Per Year for Results



Source: FALCON Project

Figure 102: Secklow Gate to 2050 - All Scenarios Metrics Over Time



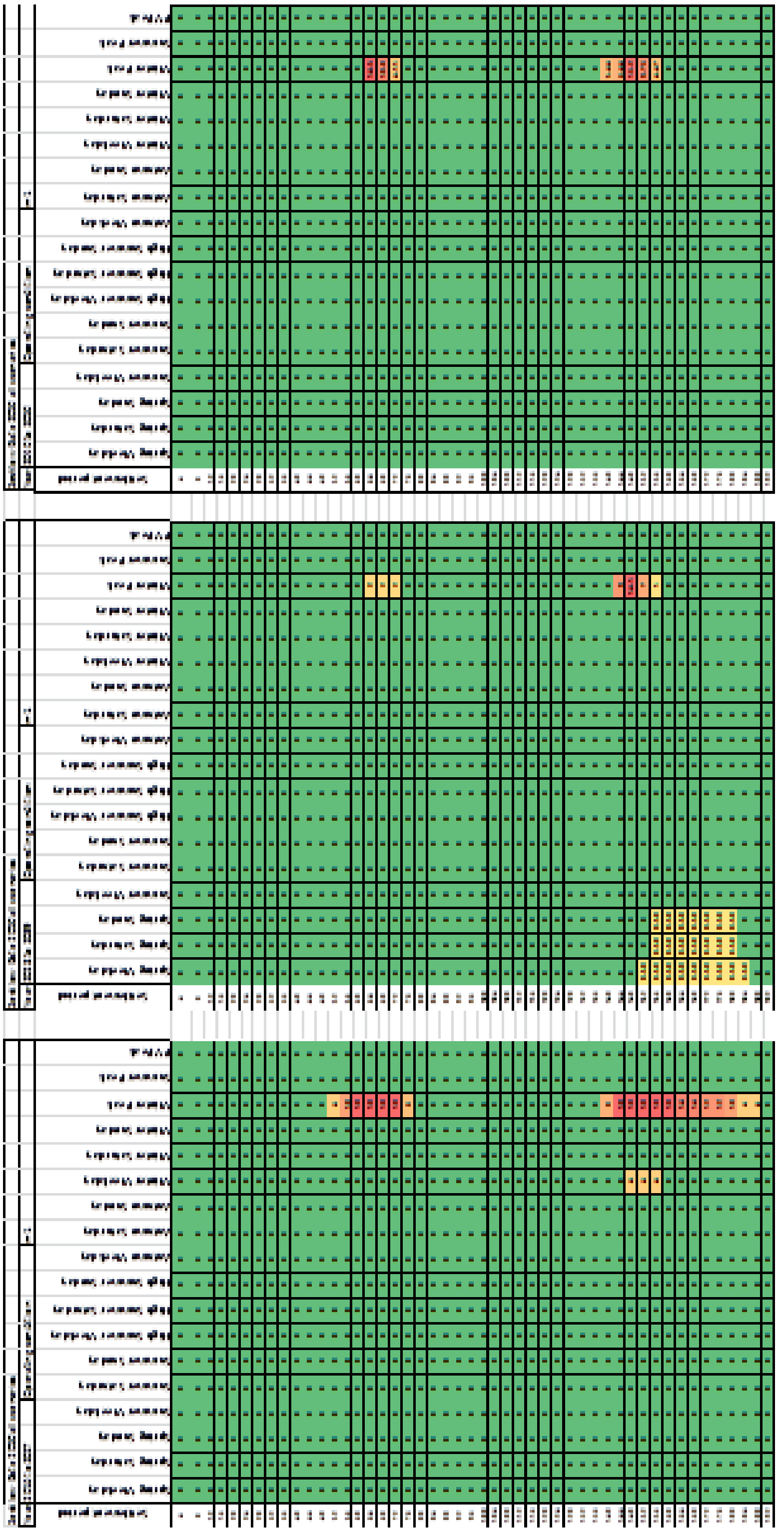
Source: FALCON Project

Secklow Gate DECC1-4 aggregated - all techniques			
		Proportion of	
Technique Name	Number	Installations	CAPEX
DAR(Cable)	11	17%	4%
DAR (Transformer)	12	34%	17%
ALT	21	0%	0%
Mesh	31	7%	2%
Batteries	41	0%	0%
DSM	51	0%	0%
DG	61	0%	0%
Transformer replacement	71	22%	41%
Cable / line upgrade	72	18%	28%
Transfer load to adjacent feeder	73	0%	0%
New feeder	74	2%	8%

No failures in 2015 with few failures appearing in other years, mostly for winter peak.

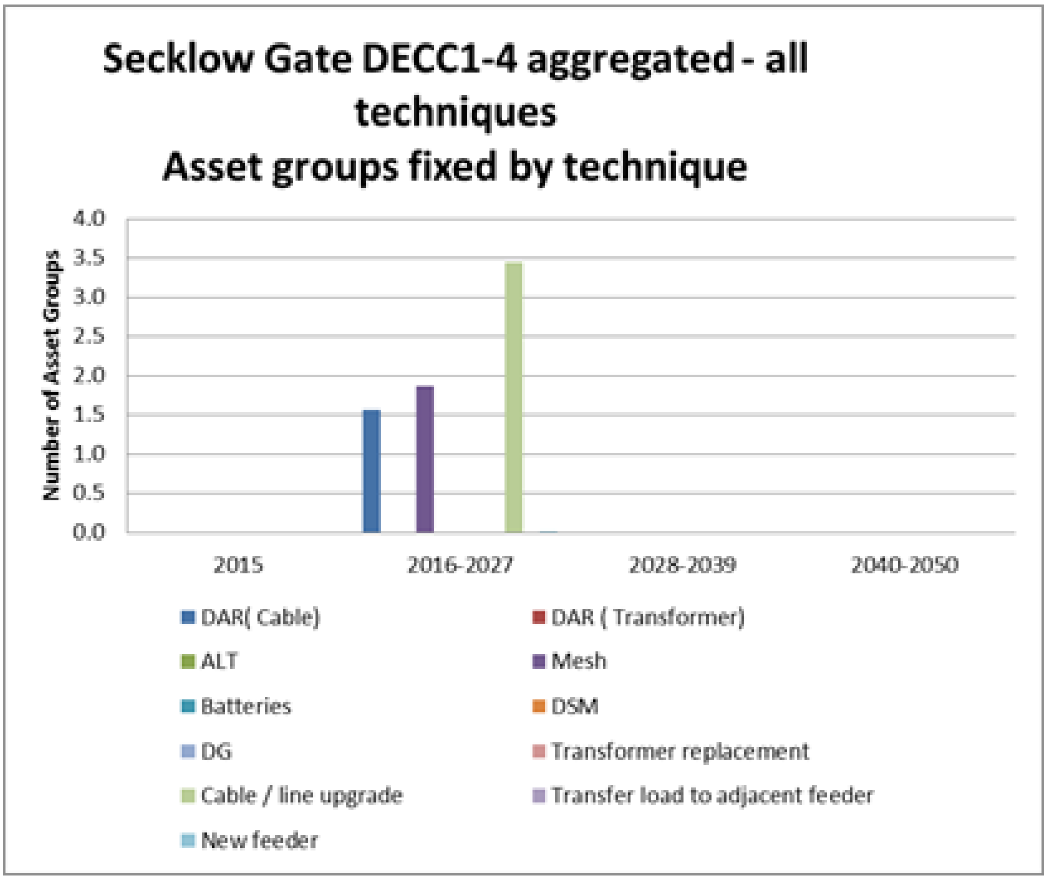
A.1.12 Timing of Issues

Figure 103: Secklow Gate - Timing of Issues - 2016 - 2050



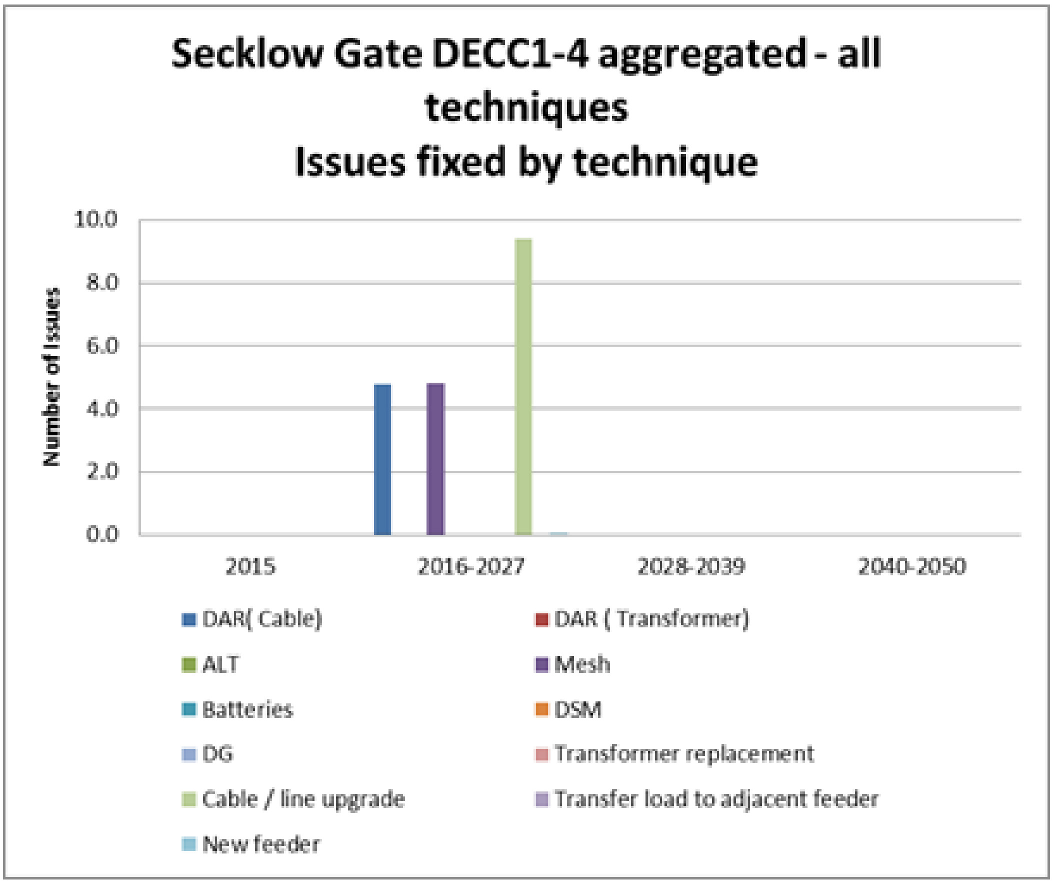
Source: FALCON Project

Figure 104: Secklow Gate DECC1-4 Asset Groups Fixed by Technique



Source: FALCON Project

Figure 105: Secklow Gate DECC1-4 Issues Fixed by Technique



Source: FALCON Project

Western Power Distribution (East Midlands) plc
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