REPORT

Development of the Transform Model for Northern Ireland

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Executive summary

Northern Ireland, in common with the rest of the UK and many other countries, is facing significant uncertainty with regard to the potential uptake of new low carbon technologies such as solar photovoltaic generation, heat pumps, distributed storage and electric vehicles. These new customer-side technologies will pose different challenges and opportunities for the electricity distribution networks over the coming years as they will drive changes in consumption patterns, customer behaviours and the operational management of the networks themselves.

Predicting the speed and geographic spread of uptake of such technologies is inherently challenging; what is certain is that the uptake will not be uniform across the country and these technologies will have different impacts for different network types (such as those in a rural or urban context). The decisions taken by a network operator in the next few years can have a material impact on the ability of the networks to take advantage of the opportunities and respond to the challenges and the associated costs of so doing.

This report describes the development of the Transform Model for Northern Ireland; a comprehensive model that is designed to assist key stakeholders in the evaluation of options to address these uncertainties and to allow exploration and quantification of many ‘what-if’ scenarios with regard to future network demands. The purpose of the model is not to provide a single definitive answer to the question of the level of investment driven by low carbon technologies going forward for NIE Networks, but rather is to provide a framework for the evaluation of options and a common base for industry dialogue on the subject.

A summary of the Transform Model key findings is presented below.

Key Conclusions

Uptake of low carbon technologies likely to have material impacts

The analysis shows that the customer uptake of low carbon technologies leads to marginal investment requirements running into £78m - £370m in discounted totex terms over the period to 2060. Figure 1 below shows the likely investment levels arising directly from differing uptake levels of low carbon technologies (low, central and high) and for different investment strategies.

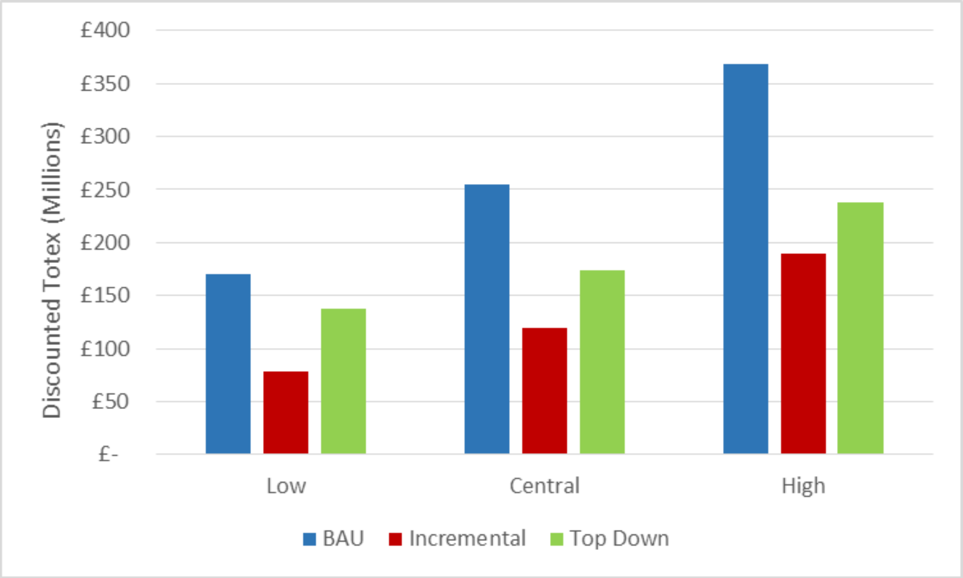

Figure 1 **Low carbon technology driven distribution network investment – discounted totex over the period 2016 to 2060 for different uptake levels and investment strategies**

It is possible to invest 'conventionally' using only those solutions that are well defined and currently business as usual (new transformers, cables, overhead lines etc.), or to adopt a 'smart' investment strategy and address the problem incrementally, or via a wholesale top down approach. The relative costs of these differing approaches are given in Figure 1.

It should be noted that the Transform Model only addresses low carbon technology related expenditure going forward. However, the model uses base loads from recent data to illustrate the level of headroom present today. This has shown that there are cases where this headroom is low, leading to some investment in the early years of the modelled period to ensure that rural networks can support network demand during outage conditions.

There is uncertainty regarding uptake, and therefore, investment levels

One of the key strengths of the Transform Model is its ability to consider a range of scenarios. Scenario based modelling is well-suited to subjects where a considerable degree of uncertainty exists, such as this case where the precise levels of uptake of, for example, electric vehicles, cannot be accurately stated.

It is therefore important to understand the likely bounds of this investment so as to be able to manage the uncertainty between the upper and lower bound. This can help inform strategic business positioning, such as decisions taken in the shorter term, which can have implications for the longer term. For example, investing a little more in the network today may allow for far greater opportunity for the network to respond in the future to meet the demands imposed by a sudden upsurge in electric vehicle uptake, whereas an equally valid technical solution to meet today's requirements, may not allow such flexibility and lead to a far greater 'whole life' cost. These aspects may raise important considerations for regulatory frameworks, and are likely to have consequences for consumer service quality and bills. A well-founded and consistent approach to scenarios, data and modelling can be expected to form a helpful basis for dialogue with regulators, customers and wider stakeholders.

Adopting smart solutions can help reduce this risk

There are different ways in which a network operator can invest in order to meet the challenges created by the uptake of low carbon technologies. The conventional approach is to install new assets (such as transformers, overhead lines, and underground cables) as and when the network requires reinforcement. In this way additional capacity is created in the network to cater for the increased demand. Such investments tend to produce significant step-increases in capacity, but sometimes with significant costs and installation times.

It can be seen from Figure 2 below that adopting a conventional approach results in a significant level of uncertainty between the three scenarios as we progress through the timescale (i.e. the three lines diverge meaning that by 2030, there is a spread of £70m). By contrast it may be possible to adopt a 'smart' approach of combining new traditional assets with a mix of innovative smart solutions or processes (such as dynamic rating, active network management, demand side response etc.). The figure below also demonstrates that in taking this approach the divergence between the scenarios is far less (approximately £28m at 2030), meaning it is easier to flex to cater for step changes in uptake of low carbon technologies.

It can also be seen that there is little difference between the investment strategies in the short term. Indeed over the first 6 – 8 years of the modelled period the investment level remains fairly manageable at an average of around £3m per annum, invested in conventional solutions. However, if continuing with the conventional approach, beyond this the annual investment requirement increases significantly to around £7m in the early-mid 2020s as the projected uptake of technologies increases and the available capacity within the network is eroded. By adopting and implementing smart solutions alongside the conventional interventions, it is possible to limit this expenditure to around £3m per annum.

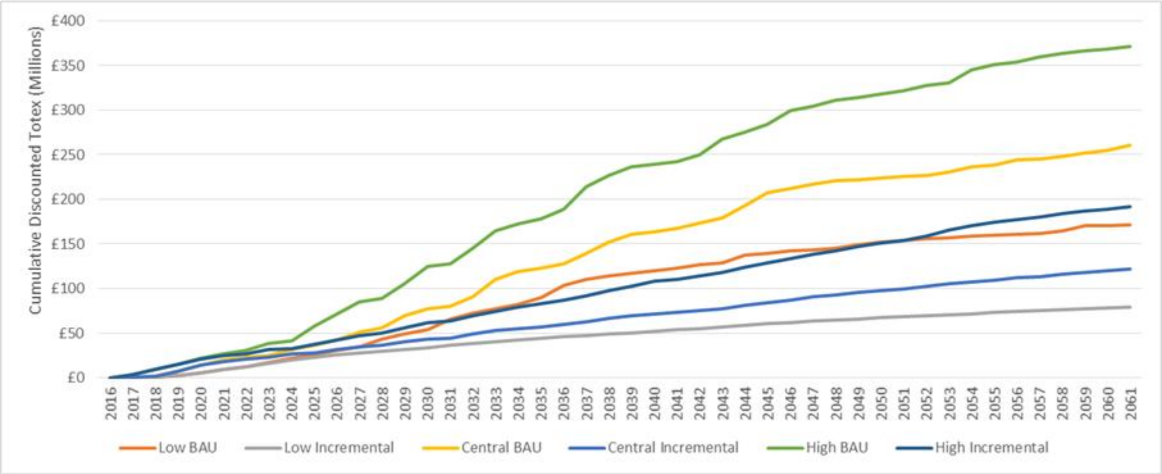

Figure 2 **Distribution network investment uncertainty**

Realising these benefits requires investment in the short term

While the results outlined in Figure 1 suggest that the investment levels if adopting a smart approach can be far lower than those utilising the conventional approach, it must be noted that this smart investment represents something of a best case scenario. It assumes that all smart intervention techniques can be deployed at scale by NIE Networks as soon as they are required or they become available on the market. The model has been configured such that these techniques are available in or around the early 2020s.

In reality, before any of these approaches can be deployed, they will have had to have been subject to a full process of trialling, testing, policy development and subsequent integration to business as usual. Such a process typically takes a minimum of 3 – 5 years to be fully integrated within the business. If such a process can be commenced as soon as possible, this means that a number of the smart solutions can then be available and ready to be deployed when the uptake scenarios start to significantly increase and associated investment levels do likewise (in approximately 6 - 8 years' time). However, if the research, development and demonstration of such approaches is not carried out ahead of this increase in uptake, then the potential benefits of adopting these approaches will be deferred significantly, leading to higher investment requirements.

Sensitivity studies are an important use-case of the Transform Model

The Transform Model allows the exploration of various sensitivity studies and the wide range of variables that can be considered make this an important use of the model when considering business strategy. A number of detailed sensitivities are considered in the full report, but some of those aspects to which the model can be found to be most sensitive focus around the nature and the location of the low carbon technologies.

For example, one can foresee that the uptake will not be uniform, but it is difficult to forecast exactly what level of local clustering will exist. By varying this clustering level within the model to a higher degree, the required investment when adopting a smart investment strategy can increase by 5% (or indeed reduce by up to 27% with less prevalent clustering). Similarly, it is not easy to forecast the charging behaviour of customers using electric vehicles. By changing the assumptions around whether there will be time-of-use incentives to charge off-peak, the investment level can vary by more than 30%.

A smart approach does not preclude conventional asset deployment

It is important to note that when adopting a smart approach, the Transform Model selects the solution that delivers the best value for money to mitigate a network threshold violation. In other words, it is not the case that the default option for the model is to utilise a smart technology intervention; as with practical business decisions, the best solution for the purpose will be identified.

This means that in the smart solutions world a large number of conventional assets are still deployed. Indeed, some of the changes in investment profile that arise are as a result of a smart intervention being used to defer the need for large investments in new conventional assets by a number of years. This indicates that the conventional assets are still required, but later in the modelled period; it also demonstrates how smart technologies can be used to provide flexibility, deferring the commitment to a more costly and complex investment until there is greater certainty. A particular characteristic of low carbon technologies is that they can assist network constraints as well as exacerbate them (depending on the mix of new demand, generation and storage) so the 'reinforcement year' is a less well-defined parameter than in the past.

Figure 3 show the breakdown of investment between conventional solutions, smart technology solutions and enablers when adopting a ‘smart incremental’ approach. Enablers are technologies that are necessary to deliver the functionality of smart solutions. For example, a dynamic rating solution requires current monitoring, communications links and ambient condition sensors to allow it to function. Individually these enablers do not ‘solve’ the problem, but without them the smart solution cannot be implemented. It can be seen that even in adopting a smart strategy, two thirds of the expenditure remains on conventional assets, partly owing to the fact that they tend to be larger investments than the smart solutions or enabling technologies.

It is noticeable that investment is still dominated by conventional solutions. This is to be expected as all the early investment (when discounting has a very small effect) is on conventional assets and, as described above, the smart solutions often defer the conventional investment to a later date in the modelled period, meaning that the conventional spend is ultimately still required, but perhaps 10 or 15 years later.

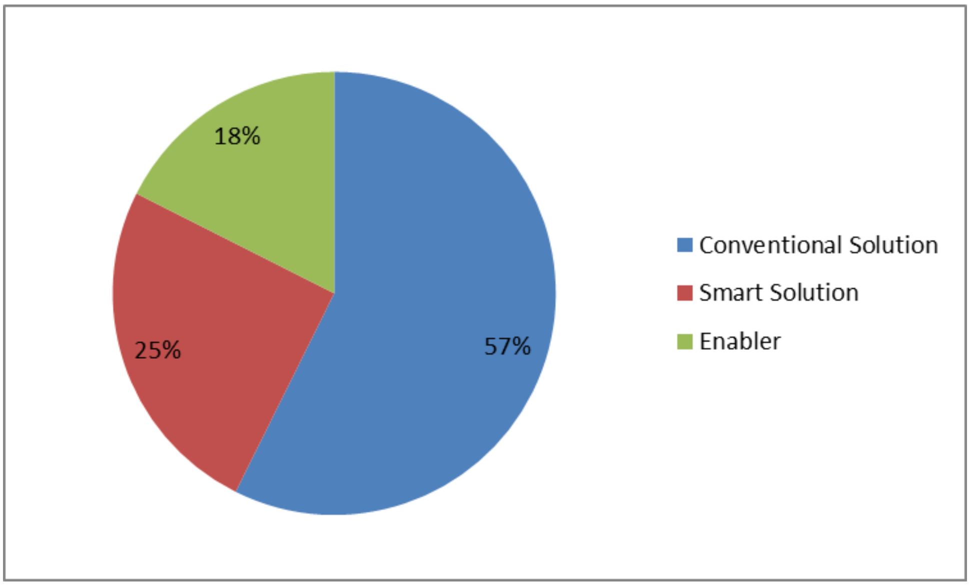

Figure 3 **Split of investment by solutions and enabler categories under ‘smart incremental’ strategy for central uptake scenario to 2060**

The Transform Model informs wider business impacts and strategy

The trialling and deployment of innovative smart solutions on networks requires a different skillset to the deployment of conventional assets. The Transform Model quantifies the level of each of these solutions to be deployed as a consequence of low carbon technologies connecting to the network, which in turn informs future skills requirements and the potential need for partnerships and service provision.

Furthermore, the Transform Model can help target future innovation approaches and trial requirements as the model indicates the likely smart solutions that will deliver best value within the Northern Ireland network in responding to the increased level of low carbon technologies. Those smart solutions that are deployed most often, or that are relevant to the network areas indicated as being most prone to overloading, can then be prioritised for further investigation and development. This ensures that any trials that are initiated can have the best chance of delivering a quantifiable return on investment by assisting NIE Networks in investing in efficient networks going forward.

As the low carbon technologies tend to connect at low voltage, it might be expected that the majority of investment requirements occur at this voltage level. Indeed, initially a reasonable amount of the investment is seen to be at LV.

However, looking upstream, it can be seen that at the HV level, a reasonably large number of LV assets aggregate onto one HV circuit (or substation). As such, many small incremental changes in demand at LV aggregate to a more significant increase at HV, driving a large amount of the investment. This explains why the Transform Model predicts that the majority of investment will occur at the HV level.

The model apportions transformer capacity across the number of circuits that the transformer supplies. In many cases, a large number of circuits are dependent on a single transformer, which means the model indicates that it is at this transformer (or substation) level that the majority of the investment is required, rather than at a feeder level. Therefore trialling and investment in novel solutions is likely to deliver the greatest return if these solutions focus on the areas which will see the greatest challenge (i.e. substations at the HV level).

In conclusion

This project has seen the creation of a Transform Model for the Northern Ireland electricity distribution system that allows users to examine a range of potential ‘what-if’ scenarios relating to low carbon technology uptake and consequential network investment requirements. It is based on data from NIE Networks and reputable public sources and is intended to assist the key stakeholders in evaluating a range of options to meet the challenges associated with the emergence of these customer-side technologies. It allows a common framework for dialogue, and can readily be refined over time as more detailed information regarding uptake levels of technologies and the availability of new solutions to manage these technologies’ demands becomes available.

The modelling shows that to accommodate the impact of low carbon technologies on the customer side, a mix of conventional network investments and smart technology investments will provide the most economic solutions for addressing distribution network constraints. The modelling also shows that such a mix is likely to provide greater flexibility and so offer strategic choices in managing the uncertainties associated with such technologies, such as the timing of tipping points and the potential for clustering that creates network constraint hot spots.

The ongoing use of the results of this model and further analysis of different scenarios can be used to directly inform NIE Networks’ business planning and strategy for accommodating the increase in low carbon technologies in an economically efficient manner while not compromising the integrity of the network from an engineering perspective.

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Appendices

1. Introduction

1.1 Context

As part of its approach to the next regulatory price control, NIE Networks is seeking to understand in greater detail the likely changes to customer demands that will be brought about through adoption of new low carbon technologies (sometimes termed ‘edge technologies’). In this way, it will also be possible to gain an appreciation of the way in which network demands will evolve and how best to ensure the network is equipped to meet the needs of customers both in the short-term, and also longer-term future.

To help achieve this, NIE Networks commissioned EA Technology (and its partner in this work, Element Energy) to investigate the likely uptake levels of various technologies and examine their effects on network loads and hence investment. In order to do this, EA Technology has created a Northern Ireland version of its Transform Model (a tool that has already been extensively used in Great Britain and in New Zealand) to quantify the challenges associated with the transition to a lower carbon future.

1.2 Aims and objectives

This report aims to provide a comprehensive understanding of the techno-economic impacts associated with the integration of low carbon technologies in Northern Ireland’s electricity distribution network. Specifically, this work can be divided into two main objectives:

- To develop the Transform Model for the strategic investment planning assessment of the electricity distribution network in Northern Ireland.
- To identify, quantify and assess the effects of low carbon technologies on the planning and development of the Northern Ireland electricity distribution network.

1.3 Scope of work

This work evaluates future investment requirements in distribution network assets associated with the integration of low carbon technologies as a result of customer behaviour changes. In this respect, this work does not consider any other types of load-related expenditure (e.g. primary reinforcement schemes, fault level reinforcement, etc.) nor core network investment expenditure owing to asset renewal, refurbishment, civil works, etc.

The strategic investment planning assessment of NIE Networks’ electricity distribution network is performed on three distinct scenarios representative of the future growth of low carbon technologies in Northern Ireland. The scenarios have been developed as part of this work and represent a well-researched central case, with an upper and lower sensitivity around this central case, reflecting the fact that uptake rates may change dependent on policy signals, consumer attitudes or market forces.

1.4 Structure of the report

This report details the method, impact analyses and key findings applied and developed by EA Technology in this work. The structure of this report is as follows:

- Section 2 presents the main structure of the Transform Model used in this work for the strategic distribution network investment and planning assessment of the electricity distribution network in Northern Ireland.
- Section 3 briefly introduces the scenarios describing the future growth of low carbon technologies in Northern Ireland.

- Section 4 provides an overview of the process adopted to develop a representative network of the Northern Ireland electricity distribution network.
- Section 5 details the sets of engineering solutions/technologies that can be deployed to resolve network constraint problems.
- Section 6 investigates the techno-economic impacts associated with the integration of low carbon technologies in the Northern Ireland electricity distribution network.
- Section 7 evaluates the impact of key factors on distribution network investment.
- Section 8 discusses some of the wider strategic business implications that can be derived from the use of the Transform Model.
- Section 9 summarises the key findings of the work.

2. The Transform Model

2.1 Structure of the model

The demand for electricity on the distribution network is changing as new technologies (e.g. electric vehicles, solar photovoltaic, etc.) become an integral part of customers' lifestyle and behaviour. The increasing presence of these low carbon technologies (LCTs) in the electricity distribution networks, with fundamentally different technical and operational characteristics, will drive a dissimilar impact to that of the incumbent technologies. Hence, there is a need for NIE Networks to understand the resulting technical effects (e.g. circuit overload, circuit under or overvoltage, etc.) of the integration of LCTs into the distribution network, the associated economic effects (e.g. overinvestment, stranded assets, ineffective risk management, etc.) for the business and as a result to establish how these new distributed generation and demand technologies should be treated in the strategic planning of the distribution network.

In response to these challenges, the Transform Model will assist NIE Networks to accomplish effective strategic decision making in respect to network planning and investment by projecting distribution network expenditure owing to increasing growth of customer uptake of LCTs and distributed generation[1]. Moreover, the Transform Model will also support NIE Networks in the risk management practices within the business. Figure 4 depicts a schematic representation of the Transform Model.

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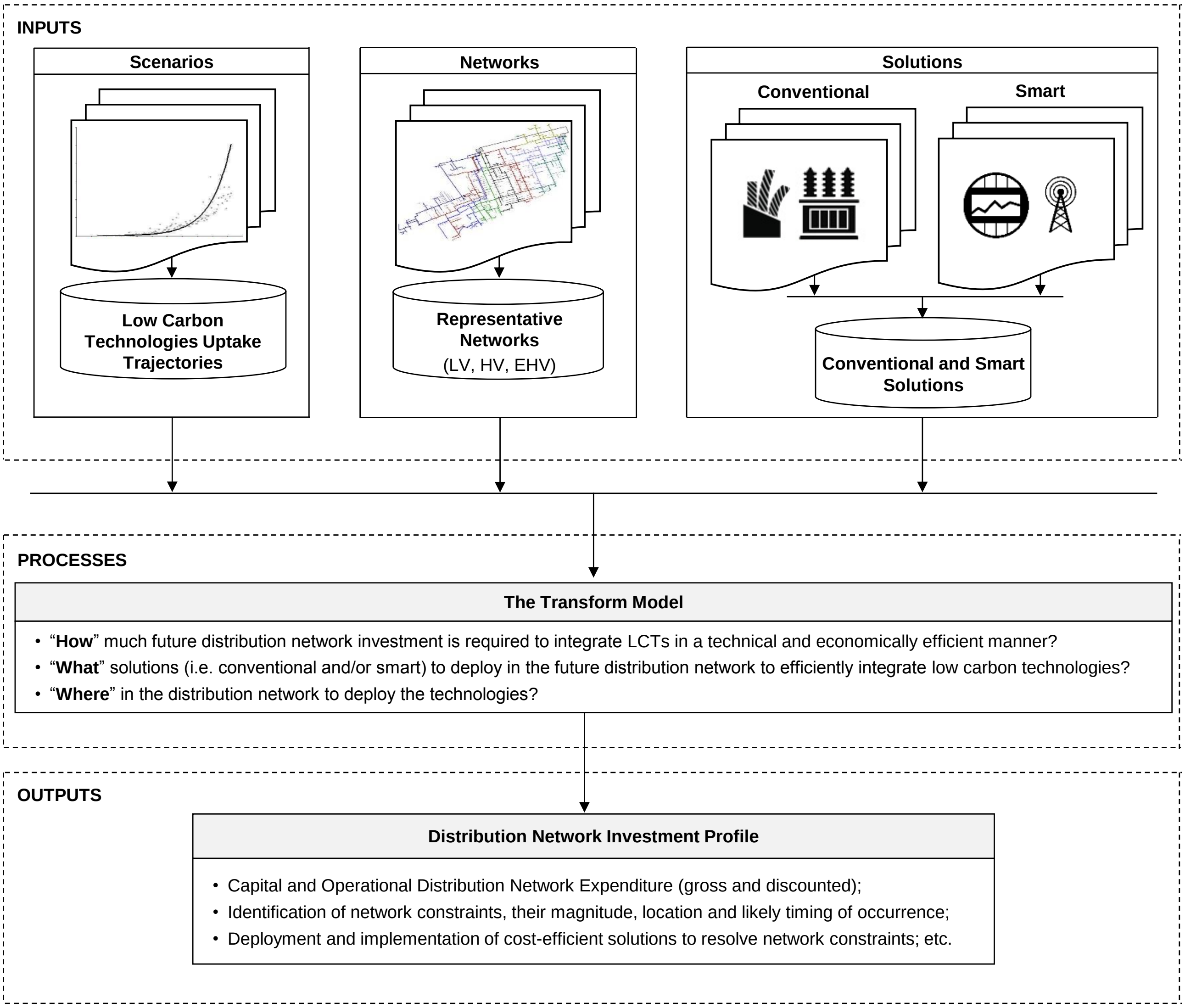
[1] It is noted that the Transform Model does not assess any other category of load-related expenditure such as zone reinforcement schemes, fault level reinforcement, network connections, etc. Similarly, the Transform Model does not assess distribution network expenditure relating to asset replacement, refurbishment, civil works, etc.



- "**How**" much future distribution network investment is required to integrate LCTs in a technical and economically efficient manner?
- "**What**" solutions (i.e. conventional and/or smart) to deploy in the future distribution network to efficiently integrate low carbon technologies?
- "**Where**" in the distribution network to deploy the technologies?

- Capital and Operational Distribution Network Expenditure (gross and discounted);
- Identification of network constraints, their magnitude, location and likely timing of occurrence;
- Deployment and implementation of cost-efficient solutions to resolve network constraints; etc.

Figure 4 **Schematic representation of the Transform Model**

Scenarios

Scenarios are used within the Transform Model to represent projections of the future electricity outlook under an uncertain landscape that is broadly driven by political, economic, social, technological and other types of uncertainty. These alternative projections of the future will enable NIE Networks and other stakeholders to better understand the effects of uncertainty and identify credible, plausible outcomes for the future of the electricity distribution network in Northern Ireland.

As part of this work, three scenarios have been defined to represent future growth of low carbon technologies in Northern Ireland. Element Energy were responsible for the creation of these scenarios which have been supplied to EA Technology for analysis within the Transform Model. The scenarios are referred to as "Central" (a thoroughly researched and well-defined scenario), "High" (a sensitivity allowing for greater uptake of technologies) and "Low" (a sensitivity assuming lower uptake rates of technologies). The development of these scenarios is discussed further in Section 3.

Networks

Real distribution systems are characterised by a vast diversity of topologies, customer densities and ratings of the feeders resulting in every feeder being different in some detail to every other feeder, even if only slightly. Attempting to model such an extensive distribution system on a circuit-by-circuit basis to assist the strategic decision making process of distribution businesses becomes an impractical task. Accordingly, the Transform Model relies on the concept of 'representative' networks to create a number of 'typical' feeders that constitute a best fit to a specific group of real feeders. Representative feeders were initially defined for NIE Networks based on real feeder data.

Then, these local representative feeders were combined and replicated in the appropriate proportions, to create an overall network that is a reasonable approximation of the NIE Networks distribution network. The development of the representative networks, that forms the NIE Networks electricity distribution network, required the collection of appropriate numerical data and set of construction principles, based on standard design practices that were provided by NIE Networks. The attractiveness of the approach described is partially attributed to the fact that the required data sets are either available or could be made available with reasonably low effort.

Solutions

Networks are made up of a range of technologies that are applied in different combinations and at different geographical scale to enable the transfer of energy from grid exit points to consumer load points. The solutions deployed by the Transform Model to resolve network constraint problems are divided in two different types:

- **Conventional solutions**: refers to technological network solutions that are widely used in the design, operation and management of current networks. Examples of conventional solutions include traditional reinforcement options such as laying new cables, replacing transformers, etc.

- **Smart solutions**: refers to new technological and/or commercial solutions that, in most cases, have not yet been widely deployed. Even technologies that are well understood, and have been trialled are considered to be smart in this framework, since they have not yet been widely deployed. These solutions can be operating on the network-side, generation-side or customer-side of the distribution system. Examples of smart solutions include dynamic network reconfiguration, dynamic thermal ratings, enhanced automatic voltage control, etc.

Model engine

The Transform Model is a techno-economic modelling tool to assess strategic investment decisions in electricity distribution infrastructures that enable the cost-efficient and secure integration of low carbon technologies in the Northern Ireland electricity system of the future. The Transform Model provides an in-depth understanding of:

- "**How**" much future distribution network investment is required to integrate low carbon technologies in a technical and economically efficient manner?

- "**What**" solutions (i.e. conventional and/or smart) to deploy in the future distribution network to efficiently integrate low carbon technologies?

- "**Where**" in the distribution network to deploy the solutions?

Outputs

The main output of the Transform Model is a network investment profile, indicating the level of expenditure required on a year by year basis to accommodate low carbon technologies in a cost-efficient manner whilst ensuring security and quality of supply as well as value for customers. The investment profile indicates the necessary capital expenditure and direct operational expenditure (such as inspection and maintenance, rental of communications channels etc) and is displayed in both gross cumulative and discounted terms to allow for ease of use when feeding into business planning. The model does not address wider requirements for investment such as asset renewal and underlying demand growth.

The Transform Model also provides numerous additional outputs such as: the identification of network constraints, their magnitude, location and likely timing of occurrence; the deployment and implementation of cost-efficient solutions to resolve network constraints; a data base of innovative network and non-network smart solutions and conventional solutions; the identification of the optimal timing for implementing these solutions; cost-estimation of the deployment of solutions in the network, etc.

2.2 Framework for distribution network investment

The Transform Model is used to quantify and assess the impacts associated with the integration of low carbon technologies in the development of electricity distribution infrastructures. The Transform Model uses the concept of 'headroom' to capture these impacts in a consistent manner. Headroom refers to the difference between the load experienced on a network or asset, and the rating of that network or asset. If the rating exceeds the load, then there is a positive amount of headroom and investment is not required. However, once load exceeds the rating then the headroom becomes negative and investment to release additional headroom must be undertaken. For the purpose of this project, the Transform Model evaluates three different types of headroom:

- **Thermal headroom**: difference between the circuit load and the thermal rating of the circuit;
- **Voltage headroom and legroom**: headroom relates to the difference between the circuit voltage at the highest point (e.g. the transformer infeed) and the upper statutory limit. Legroom relates to the difference between the circuit voltage at the end of a feeder and the lower statutory limit. Generally, the upper and lower voltage statutory limits differ by voltage level.
- **Fault level headroom**: difference between the fault level experienced at a busbar and the associated fault rating of the switchgear at that busbar. Generally, the fault level ratings differ by voltage level.

The advantage of using this concept of headroom is that it allows thermal, voltage and fault level to be discussed simultaneously on a common base. For instance, if a particular low carbon technology contributes to a reduction in both thermal and voltage headroom then this can be easily identified.

The increasing presence of low carbon technologies (as well as any organic growth in demand) generally leads to a reduction in headroom on each feeder. When thermal, voltage or fault level headroom (or voltage legroom) on a feeder reaches a pre-specified threshold (i.e. intervention threshold), the Transform Model looks to deploy the most economically efficient network solution (i.e. conventional or smart) to increase the available headroom to adequate levels. Figure 5 provides an illustration of this process. It is noted that, while the diagram only indicates thermal headroom, the Transform Model will simultaneously be ensuring that voltage headroom (or legroom) and fault level headroom are within acceptable limits.

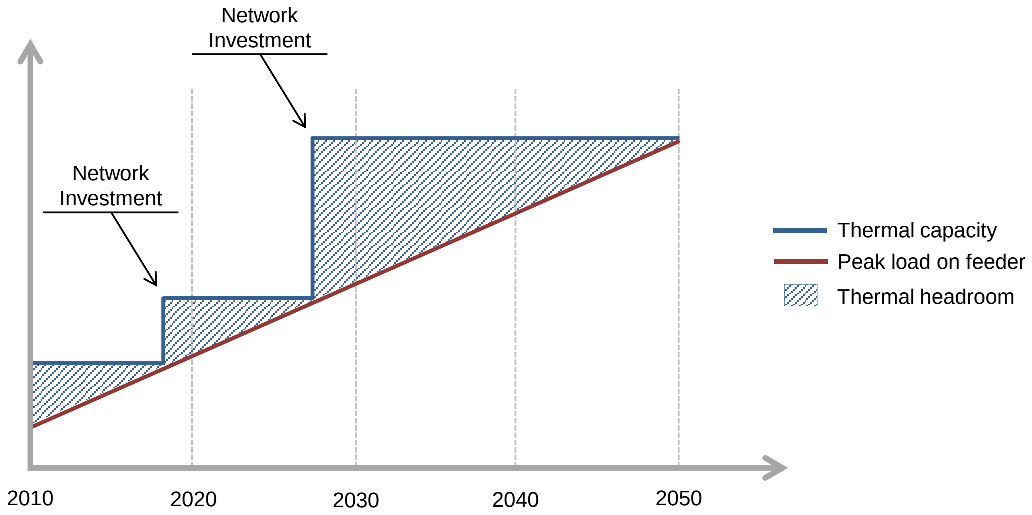
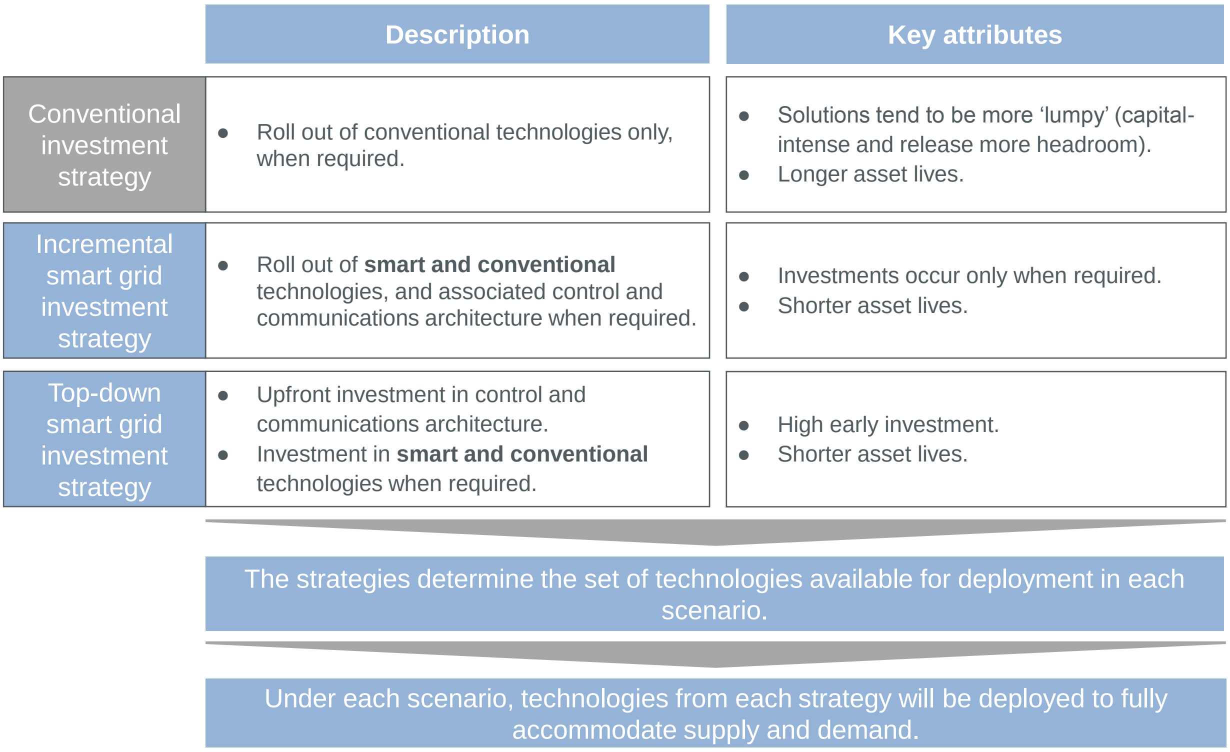


Figure 5 Illustration of the network investment process

The development of future electricity distribution networks is likely to be achieved through a mixture of conventional and smart network solutions that are deployed in different combinations and at different geographical locations to enable an economic efficient and secure delivery of electricity to customers. In this context, the Transform Model includes three distinct strategies for investment in distribution network assets. These are divided into one conventional investment strategy and two smart investment strategies all introduced in Figure 6. It is noted that each strategy entails enough investment to at least maintain the current levels of security of supply.



	Description	Key attributes
Conventional investment strategy	• Roll out of conventional technologies only, when required.	• Solutions tend to be more 'lumpy' (capital-intense and release more headroom). • Longer asset lives.
Incremental smart grid investment strategy	• Roll out of **smart and conventional** technologies, and associated control and communications architecture when required.	• Investments occur only when required. • Shorter asset lives.
Top-down smart grid investment strategy	• Upfront investment in control and communications architecture. • Investment in **smart and conventional** technologies when required.	• High early investment. • Shorter asset lives.

The strategies determine the set of technologies available for deployment in each scenario.

Under each scenario, technologies from each strategy will be deployed to fully accommodate supply and demand.

Figure 6 **Conventional and smart grid investment strategies**

The distribution network investment strategies are described as follows:

- **Conventional investment strategy**: this strategy is the only one that addresses conventional technologies exclusively. These technologies are widely used in the design, operation and management of distribution networks today. These technologies will be included in the strategy as required on each feeder type, with the lowest cost out of the conventional solutions being chosen first.

- **Incremental smart grid investment strategy**: in this strategy smart and conventional technologies will be included as required on each feeder type, with the lowest cost solutions being chosen first. This strategy does not include an upfront investment in control and communications infrastructure. Because this infrastructure is not in place, ongoing investments in smart technologies cost more than under other 'smart' investment strategies.

- **Top-down smart grid investment strategy**: smart and conventional technologies will be included in this strategy as required on each feeder type, with the lowest cost solutions being chosen first. This strategy entails an initial investment in selected control and communication infrastructure to support smart solutions in the future. The initial investment has the effect of reducing the cost of ongoing investment in smart solutions, because the costs of installing communications and monitoring equipment have already been borne in the top-down investment.

2.3 Provenance of the Transform Model

2.3.1 Initial development

The Transform Model was originally conceived through a project carried out for the Smart Grid Forum in Great Britain. This forum, chaired by DECC and Ofgem, has a number of workstreams that seek to determine how to make the transition to a smarter grid across the entire electricity sector.

Workstream 1 constructed scenarios for potential uptake rates of different low carbon technologies. These uptake scenarios were then used in Workstream 2 to determine where across the value chain of the electricity sector the costs and benefits of moving to a smarter grid lay. A basic model of networks was constructed to help determine theses costs and benefits and a key conclusion from this work was that the area of the value chain that would experience the greatest level of impact was likely to be the distribution sector.

As a consequence, Workstream 3 (facilitated by the ENA and chaired by Steve Johnson, CEO of Electricity North West) set out to create a model to determine how distribution networks would need to respond to the likely increased levels of low carbon technologies connecting over the medium – longer term. This work was supported by Ofgem and DECC (both of whom sit on Workstream 3, together with all of the GB DNOs).

Having completed the construction of this model for all of Great Britain (which came to be known as the Transform Model), further work was then undertaken to create instances of the model for each of the 14 individual DNO licence areas in Great Britain. This provided the DNOs with a tool to be able to forecast the necessary investment to accommodate LCT growth over any given timeframe, something which then lent itself to strategic business planning.

2.3.2 Use in business planning

Previously the DNOs had not had the facility to determine the level of expenditure that would be required to accommodate technologies such as electric vehicles on the network for two reasons. Firstly, such considerations had not been necessary in previous price control periods, and secondly, the uncertainty associated with where the technologies would connect and the precise rates of uptake meant that traditional approaches to network investment planning were not particularly well suited to this sort of problem.

So as to ensure that the GB DNOs could adequately support the likely uptake of such LCTs over the new price control period (RIIO-ED1, 2015-2023) and thereby positively contribute towards decarbonisation of the economy, Ofgem asked the DNOs to consider how much investment they required over the upcoming 8 year regulatory period to facilitate connection of LCTs. In order to do this, all DNOs carried out stakeholder engagement to determine which of the scenarios for LCT uptake was the most likely to emerge in their licence area over the period, and they all used the Transform Model to evaluate how much investment these scenarios would drive.

2.3.3 Ensuring the model is robust

When the Transform Model was first developed, EA Technology led a team of expert parties in its construction including those particularly experienced in understanding how load profiles will change over time, the heating requirements of different buildings and also those with significant economic expertise.

The various solutions used within the model each require costs and benefits to be attributed to them for the model to function. These were originally defined by EA Technology working in partnership with the DNOs and taking knowledge gained from trials of those solutions. In order to ensure the figures determined were sufficiently representative, an independent third party consultancy was employed to review and validate the assumptions contained within these elements of the modelling.

Further quality assurance was also carried out by DECC, a licensed user of the model, who employed a different independent party to review all of the software models that DECC uses for different purposes and this included a review of the Transform Model. DECC has gone on to use the model to evaluate the impact of potential policy decisions (e.g. to investigate the network costs associated with greater incentivisation of heat pumps).

The model has therefore been endorsed by government and also by Ofgem who describe it as 'world-leading' in its approach to this challenging area. Staff from both DECC and Ofgem have received training in the use of the model.

2.3.4 International deployment

Following the successful use of the model in Great Britain, Vector, the largest DNO in New Zealand, commissioned a version of the Transform Model and this was successfully developed in 2014. Vector has since made use of this model to forecast their expenditure owing to LCTs and to help target their innovation activities, describing their use of the model in their Asset Management Plan Update.

Following this, the New Zealand ENA sponsored the development of a model of the entire New Zealand distribution network (in the same way as the Transform model was developed for the whole of Great Britain originally). A number of DNOs in New Zealand are now using the model and there have been discussions with the regulator regarding its future use.

2.3.5 List of Users

The following is a non-exhaustive list of users who have active Transform Model licenses, split by the sector in which they operate.

- Government
  - Department of Energy and Climate Change (DECC)
- Regulator
  - Ofgem
- Distribution Network Operators
  - Electricity North West
  - Northern Powergrid
  - Scottish Power Energy Networks
  - Scottish and Southern Energy Power Distribution
  - UK Power Networks
  - Western Power Distribution
  - Vector
  - Alpine Energy
  - Buller Electricity
  - Powerco
  - The Lines Company Ltd
  - Top Energy
  - Waipa Networks
  - WEL Networks

2.4 A strategic tool

It is important to note that the Transform Model is used to inform strategic, rather than tactical, business decisions. A useful visualisation of this involves the European Smart Grid Architecture Model (SGAM)[2], which describes a smart grid approach as being made up of several 'layers', as shown in Figure 7.

The lower layers deal with the assets installed and the way in which communication occurs between these assets. The Transform Model is not prescriptive regarding the communication medium used, or the level of data warehousing that is employed, for example. Rather, the Transform Model operates at the 'function layer' providing an overall view of the way in which a smart grid should be developed to meet the needs of stakeholders and giving strategic direction to a network operator to help them achieve this.

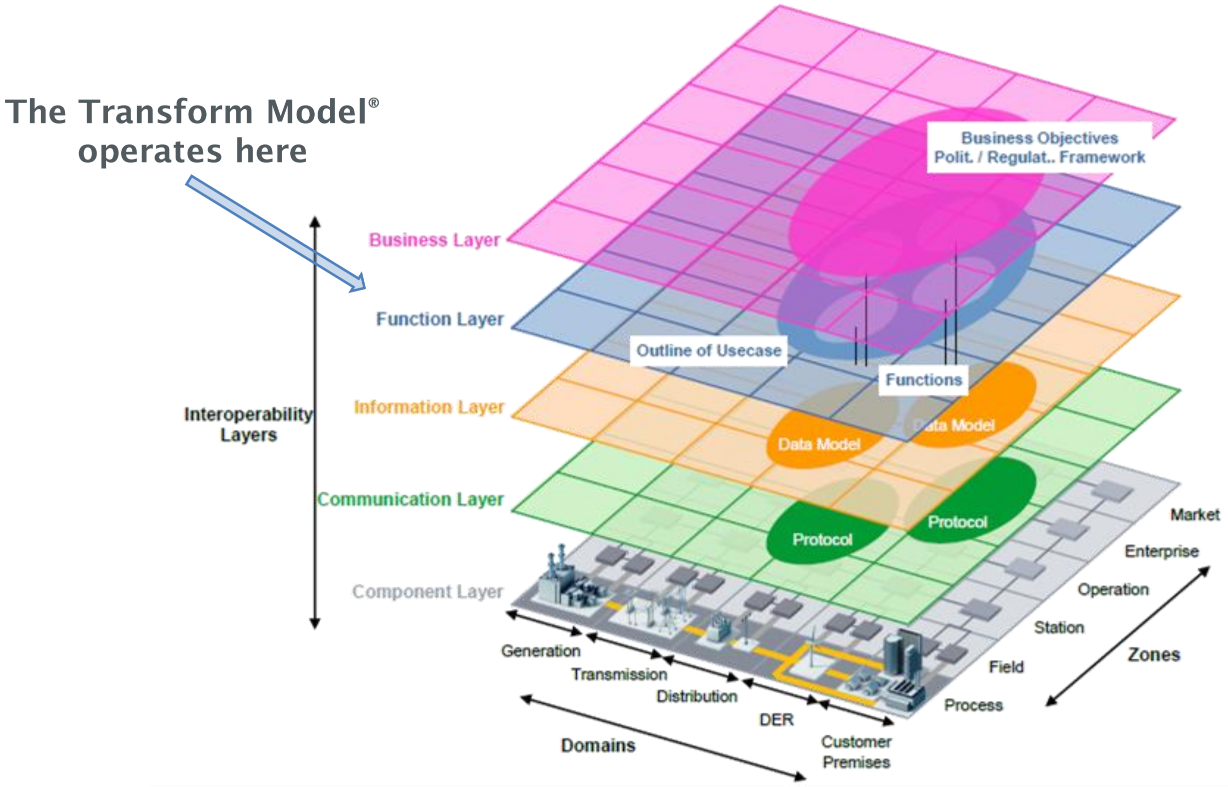


Figure 7 Smart Grid Architecture Model illustrating that the Transform Model operates at the Function Layer

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[2] http://ec.europa.eu/energy/gas_electricity/smartgrids/doc/xpert_group1_reference_architecture.pdf

3. Uptake Trajectories for Low Carbon Technologies

The evolution of electricity demand on Northern Ireland's electricity distribution system is expected to be strongly influenced by the uptake of low carbon technologies and increasing deployment of renewable generation technologies. Indeed, the last decade has already seen the energy mix starting to shift towards 'greener' sources of energy, in particular wind and solar: the total on-shore wind capacity in Northern Ireland went from circa 120MW in 2005 to 680MW at the beginning of 2015, and approximatively 80MW of solar panels were installed over the last five years. This uptake of low carbon technologies is interdependent with a number of factors, from technology costs and performance to fuel price future evolution. Over the near to medium term, it is also likely to be strongly driven by policy and government objectives, in particular incentives and regulatory support.

This section presents a set of low carbon technology uptake scenarios developed for Northern Ireland by Element Energy. For each technology considered, low, central and high scenarios were developed in an attempt to capture potential different states of the markets and national and regional objectives. All scenarios were developed for the period to 2050, although it should be noted that the projections of many of the factors that will determine the uptake become increasingly uncertain over the longer term. As a result, the study was focused on scenario building over the period to 2030, with simpler assumptions applied beyond this point.

3.1 Heat pumps

3.1.1 Policy context [3]

The Renewable Heat Incentive (RHI) was a government environmental programme that provided financial incentives to increase the uptake of renewable heat and applied to both domestic and non-domestic sectors.

The non-domestic RHI was launched in November 2011 and provides financial support for renewable heat technologies for the lifetime of the installation (for a maximum of 20 years), through an ongoing payment paid quarterly. The tariffs as of 1 April 2015 were the following: 9.0p/kWh for less than 20kWth ground source heat pumps, 4.6p/kWh for between 20 and 100kWth ground source heat pumps, and 1.3p/kWh for larger than 100kWth ground source heat pumps.

The domestic RHI was launched on 9 April 2014 and consists of two types of payments, an upfront payment and an ongoing payment, which is paid annually. Upfront and ongoing payments are currently set to £1,700 and 3.6p/kWh respectively for air source heat pumps and £3,500 and 8.3p/kWh for ground source heat pumps.

It should be noted however that the majority of RHI accreditations that were completed up to 2015 were for biomass boilers, and only a few accreditations were completed for heat pumps.

However, the RHI in Northern Ireland was suspended to new applications on 29th February 2016 and there is considerable uncertainty regarding its future. As such, the scenarios for modelling have been designed to reflect this uncertainty.

3.1.2 Modelling methodology

A consumer choice modelling methodology was used to construct heat pump uptake scenarios. A consumer choice model predicts the choice that consumers will make given a particular set of options – in this case, heating technologies – using quantitative consumer survey results as one of their main inputs (these results are from a recent survey conducted for DECC). The consumer surveys are used to assess the relative importance consumers attach to a range of attributes describing each technology choice (attributes include capital costs, ongoing costs and savings, but

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[3] https://www.detini.gov.uk/articles/renewable-heat-incentive-rhi

also include factors such as the hassle involved in the installation process, space taken up and so on). This relative importance of attributes is used to derive attribute weighting factors. The attributes and their weighting is then used to create an index of how attractive each technology is to the various consumer groups, which is then converted within the model to the share of the market that the technology will capture. On top of this consumer choice representation, the heat pump uptake derived by the model is influenced by the technical potential (i.e. number of buildings suitable), number of decision makers (e.g. based on boiler sales) and supply side constraints (i.e. estimates of industry growth rates). This logic is summarised in the flow diagram below.

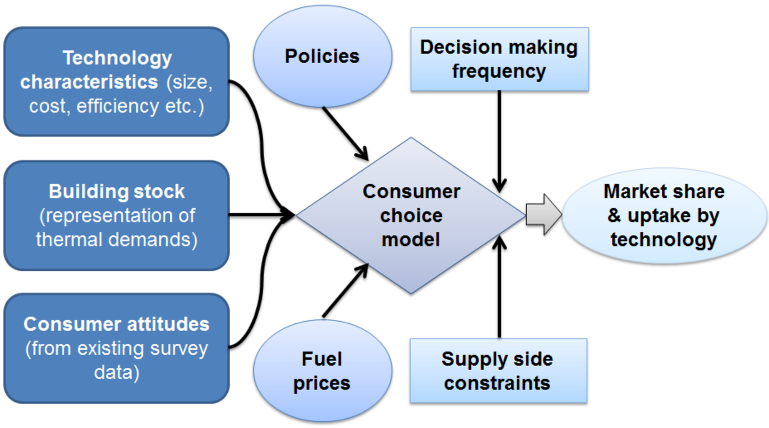

Figure 8 **Consumer choice model flow diagram**

To ensure that the models are representative of the Northern Ireland case they were populated with data reflecting the housing stock, main heating fuel and current state of technology deployment in Northern Ireland.

3.1.3 Uptake scenarios

Heat pump uptake scenarios were defined based on fuel cost scenarios[4] and the assumed availability of the RHI. The three scenarios in the DECC fuel cost projections have been used for the three technology uptake scenarios in this project, as presented in the table below. These fuel costs help determine the uptake by evaluating, for example, the likely price of gas and therefore the attractiveness of alternative heating technology.

Table 1 **Heat pump uptake scenario definition**

Scenario	Renewable Heat Incentive (RHI) availability	DECC fuel price
Low	No RHI	DECC low scenario
Central	RHI re-opens in 2018 and closes in 2022	DECC reference scenario
High	RHI re-opens in 2016 and closes in 2022	DECC high scenario

These scenarios translate into the three uptake rates illustrated in Figure 9 (domestic heat pumps) and Figure 10 (commercial heat pumps).

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[4] https://www.gov.uk/government/publications/updated-energy-and-emissions-projections-2014

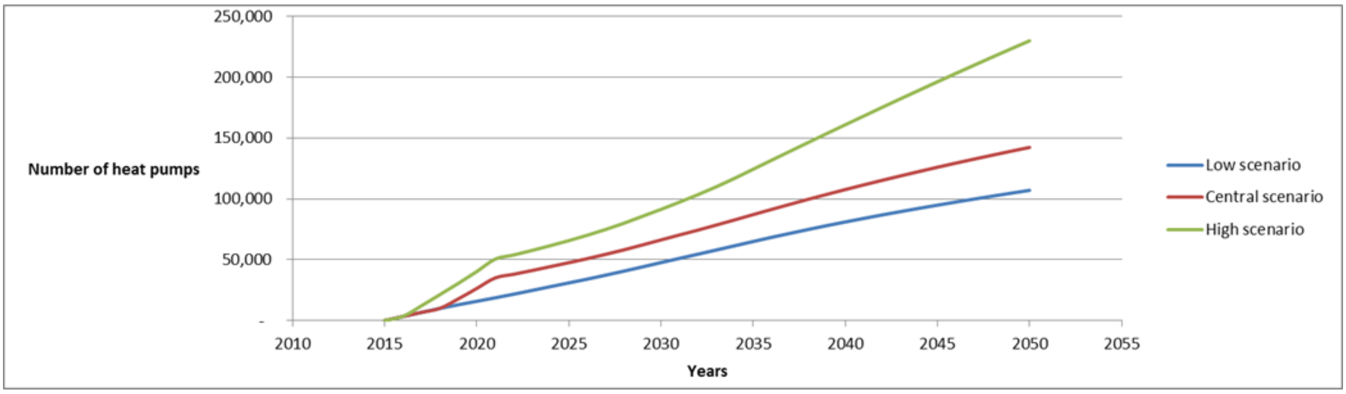

Figure 9 **Domestic heat pump uptake scenarios**

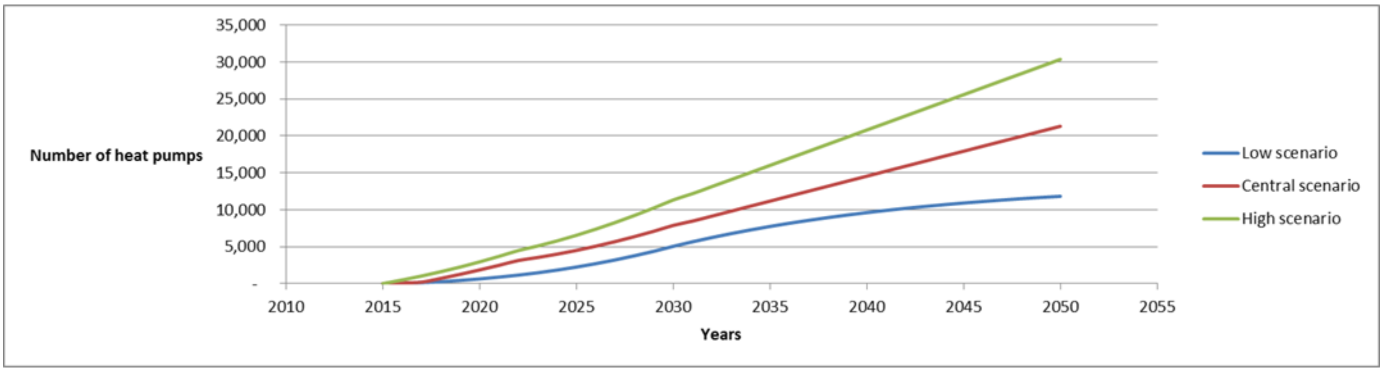

Figure 10 **Commercial heat pump uptake scenarios**

The central scenario shows an uptake of circa 70,000 domestic and 8,000 commercial heat pumps in 2030. With ~792,000 Northern Ireland Electricity domestic consumers and ~61,900 commercial consumers in 2015, and with on average ~6,650 new domestic buildings and ~650 commercial buildings each year, this uptake corresponds to ~8% of dwellings and ~11% of commercial properties.

3.2 Electric Vehicles

3.2.1 Policy context [5]

Several incentives are currently in place in Northern Ireland to support the development of electric transport, both in the commercial and private sectors:

- **Home Charge Scheme** - OLEV provides a grant up to 75% and £700 towards the cost of one charge point and its installation;
- **Plug-In car and Van Grant** - the UK government provides grants up to £5,000 towards the purchase of an electric vehicle (EV) and up to £8,000 for an electric van;
- **Incentives for business** – EVs are exempted of fuel duty, vehicle excise duty, company car tax, van benefit charge, fuel benefit charge, etc.

3.2.2 Modelling methodology

Forecasts are generated using a GB EV uptake model developed by Element Energy for the ETI and subsequently expanded and updated for the DfT. The model is a consumer choice model based on an extensive survey of consumer vehicle purchasing behaviour (this survey was conducted for DfT

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[5] http://www.ecarni.com/

and was the largest of its kind). It combines policy inputs, vehicles' attributes, and consumer purchase attitudes to calculate the uptake of different powertrains.

To ensure that the scenarios are representative of the Northern Ireland case they were populated with data reflecting the current state of the ecarNI[6] network as well as data on the Northern Ireland housing characteristics (e.g. fraction of households that are suitable to home charging).

3.2.3 Uptake scenarios

Electric vehicle uptake scenarios were defined based on the following assumptions:

- **Low scenario** – The coverage by rapid charging points stays low (10%). EU CO2 targets are unambitious post 2020: 60 gCO_2/km in 2050 versus 42 gCO_2/km in other scenarios (the average emission level of a new car sold in 2014 was ~123 gCO_2/km, i.e. less than the 2015 target of 130 gCO_2/km; the 2021 target has been set to 95 gCO_2/km);

- **Central scenario** – There is a good coverage of the country by rapid charging points, reaching 100% by 2020, and low access to local charging points (10%);

- **High scenario** – There is a good coverage of the country by rapid and local charging points (100% by 2020), plus a change in attitudes towards electric vehicles with time (consumers with negative bias are assumed to become more accepting as electric vehicle sales increase).

The resulting scenarios are presented in the two graphs below, for electric cars and electric vans. It should be noted that the level of uncertainty regarding the uptake of electric vehicles is higher for vans than for cars as it corresponds to an earlier market.

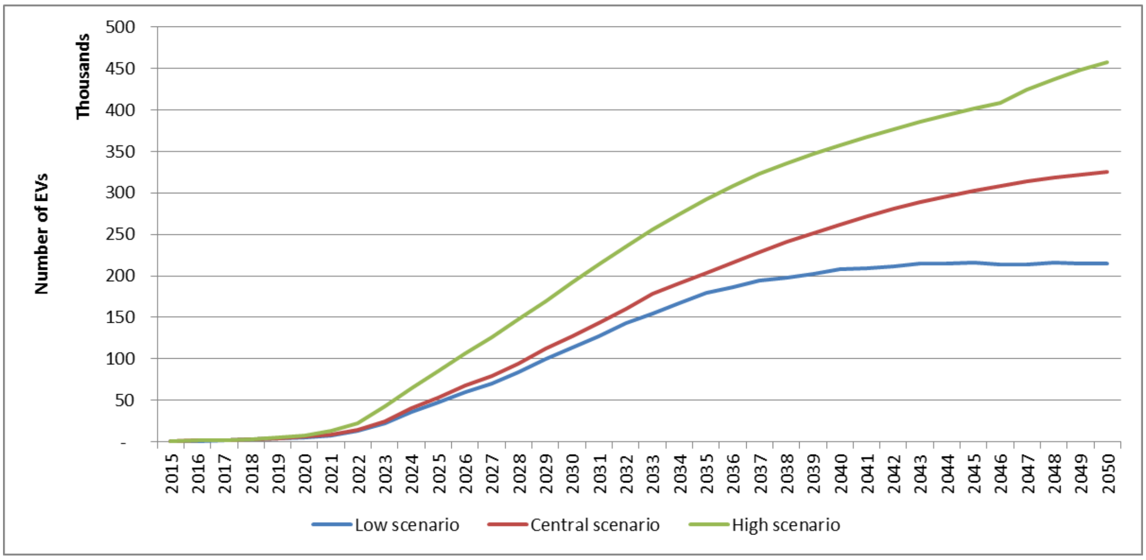

Figure 11 **Electric car uptake scenarios**

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[6] http://www.ecarni.com/

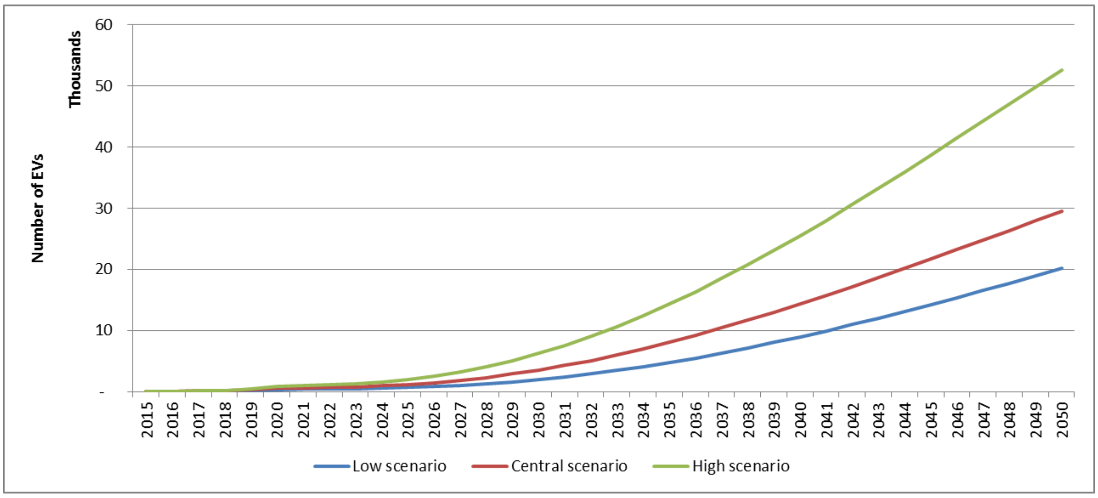

Figure 12 **Electric van uptake scenarios**

In 2013 there were ~1,067,000 vehicles in Northern Ireland, including 887,000 cars and 98,000 vans. Assuming that the future annual increase of the total number of vehicles is consistent with the increase that was seen during the last ten years, the electric vehicle uptake in the central scenario corresponds to ~15% cars and ~3% vans being electric in 2030.

Note: the split between private electric vehicles and commercial electric fleets was assumed to be similar to the current one of petrol vehicles.

3.3 Solar photovoltaic

3.3.1 Policy context [7]

Since 2005 the Northern Ireland Renewable Obligation (NIRO) has been the main incentive to support renewable energy generation in Northern Ireland. DECC quarterly published data on renewable electricity capacity and generation show that more than 80MW solar capacity was installed between 2011 and 2015 (uptake shown in the graph below). [8]

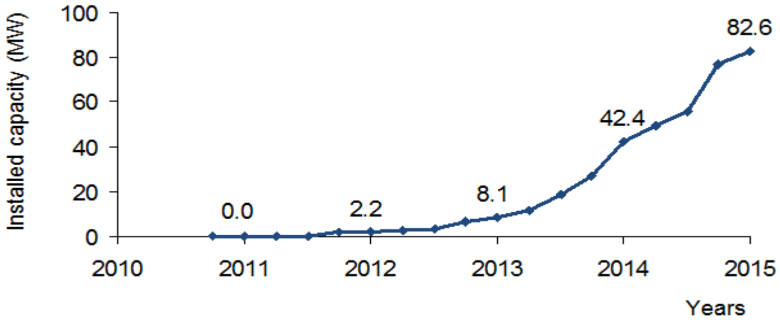

Figure 13 **PV quarterly uptake in Northern Ireland up to 2015 Q1**

The NIRO scheme will close to new generation and additional capacity of solar panels from 1 April 2017. Afterwards, large scale renewables will be supported by UK-wide Feed-In Tariffs with Contracts for Difference (from 2016), and the Department for the Economy intends to continue supporting

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[7] http://www.detini.gov.uk/northern_ireland_renewables_obligation_
http://www.detini.gov.uk/index/what-we-do/deti-energy-index/renewable_electricity-2/small_scale_fit.htm

[8] https://www.gov.uk/government/statistics/energy-trends-section-6-renewables

small scale renewables through the introduction of a small-scale Feed-In Tariff (FIT) in 2017 to coincide with the closure of the NIRO.

3.3.2 Modelling methodology

From 2015 to 2017 and the end of the NIRO scheme in 2017, the projected uptake was based on historic quarterly uptake. From 2017 and the beginning of the FIT scheme up to 2030, forecasts were generated using the Element Energy's GB feed-in tariff model. This model calculates the technical potential for installation of PV and the economics of installing PV in different kinds of installations (size of array, building-integrated versus ground-mounted, residential vs commercial). The modelling approach is based on the construction of electricity supply curves showing the size of the resource available at a given generating cost. This technical potential is combined with constraints and barriers to deployment to calculate a dynamic resource – the maximum deployment in each year. By calculating the rates of return for each technology under the FIT, the model calculates the proportion of the maximum resource that is deployed each year, based on investor hurdle rates.

To ensure that the model is representative of the Northern Ireland case it was populated with data reflecting the building stock, current state of technology deployment, and levels of insulation in Northern Ireland.

3.3.3 Uptake scenarios

From 2017 to 2030, PV uptake scenarios were defined based on the FIT assumed end year, fuel cost[9] and technology scenarios[10], as presented in the table below.

Table 2 **PV uptake scenario definition**

Scenario	Feed-In Tariff	Fuel cost scenarios	Technology cost scenarios
Low	FIT runs up to 2020	DECC Low	High price
Central	FIT runs up to 2025	DECC Reference	Reference
High	FIT runs up to 2030	DECC High	Low price

As details of the future NI FIT scheme are not yet known, the model assumes that in the first year the program will be similar to the GB FIT, and that tariffs will be reviewed quarterly. After 2030, simpler assumptions were made, i.e. a continued slow uptake in the low scenario, a continued uptake in the central scenario showing a continued slowdown in new installations per year, and a continued uptake at pre-2030 rate in the high scenario, up to a maximum value (this maximum of 800MW corresponds to the highest scenario being considered in the '2050 Vision report - Considering Energy in Northern Ireland to 2050'[11]).

As part of these scenarios, a split has been provided by installed size, showing how the uptake at both domestic and commercial level will vary. This granularity is contained within the Transform Model.

The three scenarios that were constructed using this methodology are shown in the graph below.

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[9] https://www.gov.uk/government/publications/updated-energy-and-emissions-projections-2014
[10] https://www.gov.uk/government/statistics/solar-pv-cost-data
[11] https://www.detini.gov.uk/publications/considering-energy-northern-ireland-2050

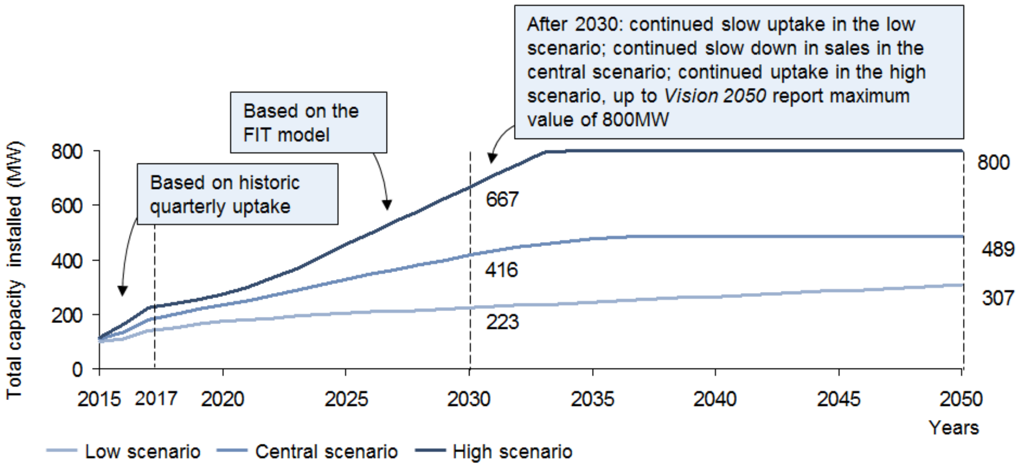

Figure 14 **PV uptake scenarios**

The potential uptake of domestic-level battery storage in conjunction with PV generation has not been considered as a scenario here. However, it is examined in the sensitivity analysis and can be configured within the Transform Model as necessary (any proportion of PV can be set to have battery storage associated with it by a user).

3.4 On-shore wind

3.4.1 Policy context [12]

As discussed in the chapter on PVs, the Northern Ireland Renewable Obligation has been the main incentive to support renewable energy generation in Northern Ireland over the last ten years. From 2016, large scale renewables will be supported by UK-wide Feed-In Tariffs with Contracts for Difference. DECC quarterly published data on renewable electricity capacity and generation show that the total on-shore wind capacity in Northern Ireland has more than doubled between 2011 and 2015 (this uptake is shown in the graph below). [13]

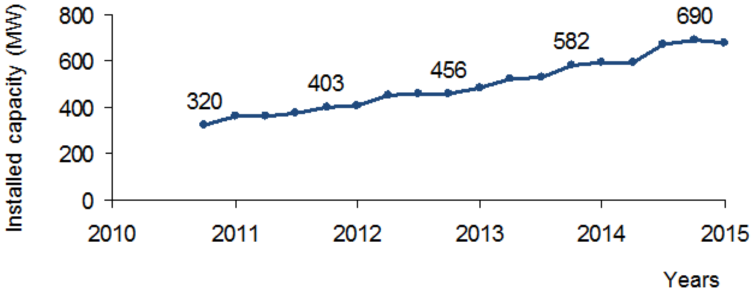

Figure 15 **On-shore wind quarterly uptake in Northern Ireland up to 2015 Q1**

To date (in October 2015), on top of already installed and operational on-shore wind installations, 190 MW are under construction, and 554 MW are consented.[14]

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[12] http://www.detini.gov.uk/northern_ireland_renewables_obligation_
http://www.detini.gov.uk/index/what-we-do/deti-energy-index/renewable_electricity-2/small_scale_fit.htm

[13] https://www.gov.uk/government/statistics/energy-trends-section-6-renewables

[14] http://www.renewableuk.com/en/renewable-energy/wind-energy/uk-wind-energy-database/index.cfm

3.4.2 On-shore wind forecasts (from the literature) [15]

The Strategic Energy Framework for Northern Ireland included a target of 40% of electricity consumption from renewable resources by 2020 and also included an interim target of 20% of electricity consumption from renewable resources by 2015. It is estimated that an installed wind capacity of circa 1,200 MW will be enough to achieve the 40% figure by 2020. It should be noted that the total capacity already installed together with the 190MW under construction and the 554MW already consented should already allow this 1,200MW objective value to be exceeded. The All-Island Generation Capacity Statement 2015-2024 report forecasts an uptake of 1,389MW of on-shore wind capacity in Northern Ireland in 2024 (this uptake is shown in the graph below), with a maximum annual uptake reached in 2015 and slowing down afterwards

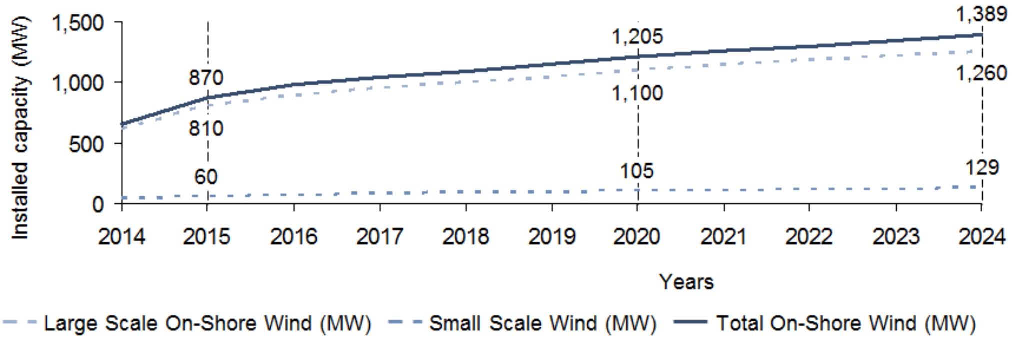

Figure 16 On-shore wind uptake forecast, from the All-Island Generation Capacity Statement 2015 – 2024 report

3.4.3 Uptake scenarios

A number of forecasts were devised, based on the All-Island Generation Capacity Statement 2015-2024 report, and assumed to slow down in on-shore wind uptake from 2016 with the closure of the Northern Ireland Renewable Obligation.

These forecasts were updated by NIE Networks in line with recently available data concerning applications for connections that had been received and the likely flattening of future growth in this area.

The three scenarios constructed by NIE Networks are shown in the graph below.

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[15] http://www.soni.ltd.uk/media/documents/Operations/CapacityStatements/All%20Island%20Generation%20Capacity%20Statement%202015%20-%202024.pdf

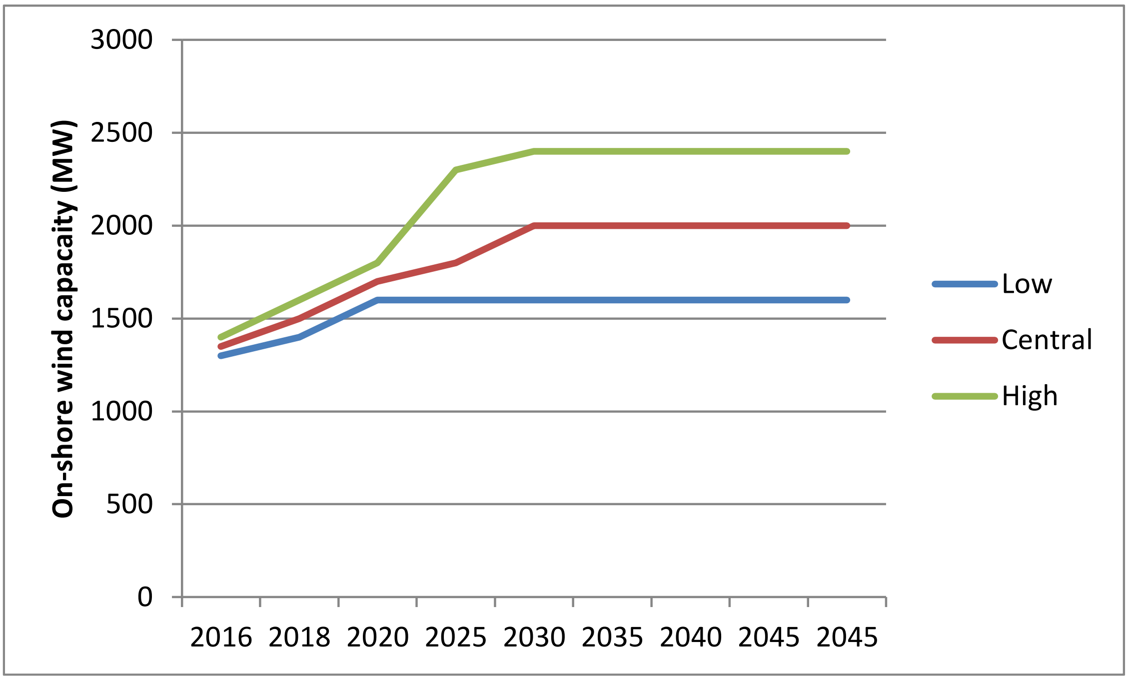

Figure 17 **On-shore wind uptake scenarios**

It should further be noted that the uptake of wind generation is included within the model so as to ensure it is representative of the total levels of demand and generation that the network will be subject to, over the coming years. Wind generation does not drive investment in the Transform Model and it is not intended that reinforcement costs associated with the connection of wind generation at, for example, 33kV are derived from or used within the Transform Model results or calculations.

4. Representative Electricity Networks

This section provides an overview of the process adopted to develop a representative network of the of the entire distribution network in Northern Ireland. It details the key characteristics and parameters of the representative feeders, specifies how these feeders are combined across the different voltage levels and discusses the way in which loads of the representative feeders were determined and examined.

4.1 Framework for representative feeders

Real distribution systems are characterised by a vast diversity of topologies, customer densities and ratings of the feeders resulting in every feeder being different in some detail to every other feeder, even if only slightly. Attempting to model such an extensive distribution system on a circuit-by-circuit basis to assist the strategic decision making process of distribution businesses becomes an impractical task. In this respect, the framework adopted to classify and characterise networks uses the concept of ‘representative’ networks to create a number of ‘typical’ feeders that constitute a best fit to a specific group of real feeders. Representative feeders were initially defined based on the real feeders found in NIE Networks. Then, these local representative feeders were combined and replicated in the appropriate proportions, to create an overall network that is a reasonable approximation of the entire Northern Ireland distribution network.

The concept of ‘representative’ networks enables the grouping of a set of real networks of similar inherent parameters such as the feeder length, configuration, construction, number of customers, etc., into a single network now characterised by ‘typical’ parameters such as average feeder length, average number of customers, etc. The framework creates a different representative network when a set of real networks have relatively different parameters since the mix and make-up are likely to be different. The use of this parametric approach, in contrast to a nodal approach, permits significant reduction of the number of feeders to model and the computation of load flows in large distribution systems. Parametric and nodal models can be defined as follows:

- **Parametric model**: uses a high level of abstraction to classify and characterise networks through their structural (e.g. construction: overhead, underground; configuration: radial, meshed; etc.), electrical (e.g. thermal rating, voltage rating, etc.) and population (e.g. urban, rural, etc.) attributes. It generally uses various types of ‘headroom’ to assess the performance of the network. Headroom is the difference between the actual power flows, voltages and fault levels and the limits set by network design, equipment ratings, or legal/regulatory requirements. Parametric models usually provide a high level of understanding and are especially well suited for strategic planning activities.

- **Nodal model**: enables the representation of a network through the detailed specification of the electrical properties of all its components through their equivalent circuit model. The performance of the network is assessed through the computation of a full load flow where the power injected in the network is directed to serve the load points.

It should be stressed that this framework allows for the representation of a ‘typical’ distribution network. It does not encompass every possible condition or topology that may occur in Northern Ireland. The development of the representative networks was driven by the data provided by NIE Networks, together with the experience of EA technology and is considered to be a sufficiently accurate representation of the network for strategic, rather than tactical, planning.

4.2 Definition of representative feeders

Representative feeders (also referred to as typical feeders) were developed such that each typical feeder is the most appropriate representation of the characteristics of a group of real feeders of the Northern Ireland distribution network. The process followed to create representative feeders can be divided into three key steps: (i) real feeder classification; (ii) representative feeder classification; and (iii) representative feeder parameterisation.

- **Real feeder classification**: this step classifies and characterises the real network feeders found within NIE Networks through structural (e.g. construction: overhead, underground; configuration: radial, meshed; etc.), electrical (e.g. thermal rating, voltage rating, etc.) and population (e.g. urban, rural, etc.) attributes. The process is driven by the data made available by NIE Networks.

- **Representative feeder classification**: this step creates a typical feeder that best represents the characteristics of a set of real feeders. In principle, each set of real feeders contains feeders which, although clearly not identical, are 'similar'. The similarity is determined by the defined range of the relevant structural, electrical and population attributes. It is noted that this step is a very crucial part of the process since if this range is too small, the number of representative feeders will become very large and the behaviour of the typical feeder could be rather dissimilar to the real feeder; but if the range is too large then the process clearly becomes more complex and difficult.

- **Representative feeder parameterisation**: this step establishes the final reduced set of typical feeders that best represent the real feeders of the Northern Ireland distribution network. Each typical feeder can be viewed as the average feeder of a particular set of similar real feeders. Furthermore, the process decides and defines the quantitative values of the inherent attributes/parameters of the typical feeder that represents the set of the real feeders.

The key structural, electrical and population attributes of feeders considered in the 'typical feeder classification' process include:

- Voltage: Low Voltage (LV ≤ 1kV), High Voltage (6.6kV and 11kV), Extra High Voltage (33kV);
- Geography: rural, suburban, urban;
- Construction: overhead, underground, mixed;
- Configuration: radial, meshed;
- Feeder thermal rating;
- Feeder length;
- Peak load; and
- Number of customers.

4.2.1 Real feeder classification

The information and data relating to the real network feeders as well as their respective structural, electrical and population attributes were provided by NIE Networks. Table 3 summarises key characteristics of the Northern Ireland distribution network as provided.

Table 3 **Key characteristics of the Northern Ireland distribution network**

Networks	Number of feeders	Number of transformers	Number of customers
Extra high voltage	265	n/a	850,732
High voltage	1,234	405 (EHV/HV)	
Low voltage	90,327	76,121 (HV/LV)	

At a workshop, EA Technology liaised with NIE Networks to define the appropriate feeder classes that would allow all elements of the NIE Networks distribution network to be considered. This then allowed for analysis of the network data that NIE Networks would provide into these various classes. The next step is then to derive appropriate parameters for these feeders.

As an example, Figure 18 and Figure 19 below show for the EHV1 circuit type (urban underground circuits) the various circuit ratings and lengths that are found in the network. It is clear from these figures that an appropriate rating for the EHV1 circuit is 525A (30MVA) as this is the most prevalent rating in the class of feeder (it represents both the median and the mode of the data). When considering the length, there are a large number of very short circuits, but relatively few above 4km. An average figure that takes into account all of the feeders is found to be approximately 2km.

This sort of analysis was repeated for all of the feeder types, thus enabling the creation of the representative parametric feeders.

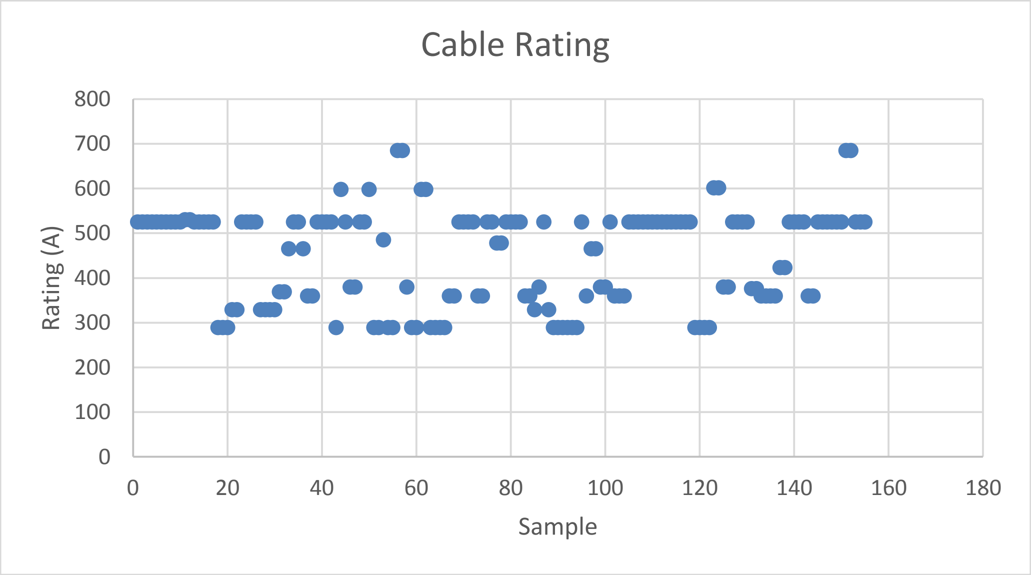

Figure 18 **Scatter plot showing the ratings of all EHV 1 (urban underground) circuits**

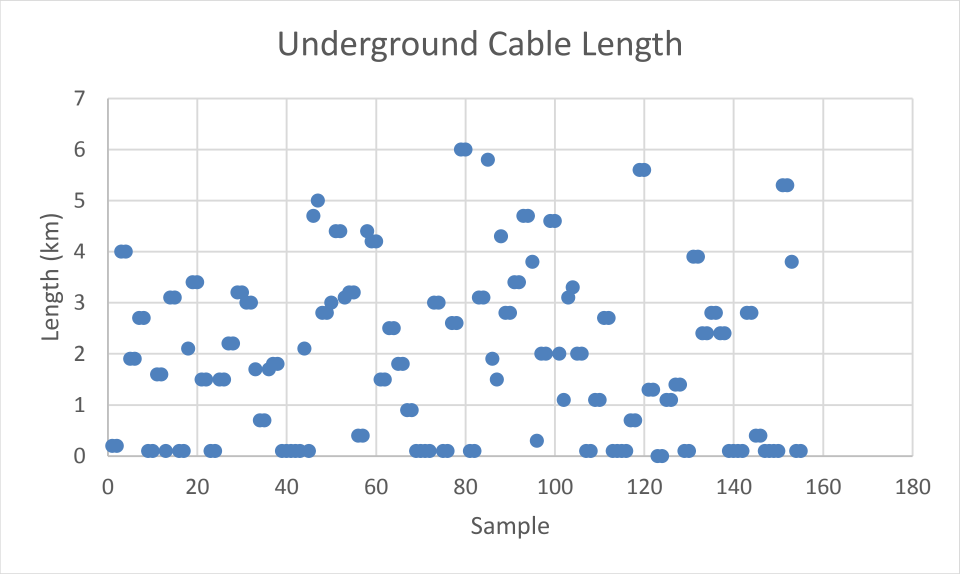

Figure 19 **Scatter plot showing the length of all EHV1 (urban underground) circuits**

4.2.2 Representative feeder classification

Having examined the data and thus derived the basic parameters for the representative feeders, the various feeder classifications can thus be summarised. The following tables illustrate this classification, providing the rating, length, peak load and number of circuits for each class across all three voltage levels.

Table 4 **Representative feeders of the EHV distribution network in Northern Ireland**

Feeder	Feeder definition	Thermal rating (kVA)	Length (km)	Peak load (kVA)	Number of networks
EHV1	Urban underground radial	30,000	1.96	6,200	21
EHV2	Urban underground meshed	34,200	2.4	9,270	21
EHV3	Rural mixed radial	16,200	12.12	5,000	125
EHV4	Rural mixed meshed	19,500	13.22	6,760	98
				Total	265

Table 5 **Representative feeders of the HV distribution network in Northern Ireland**

Feeder	Feeder definition	Thermal rating (kVA)	Length (km)	Peak load (kVA)	Number of networks
HV1	Town Centre 11kV	3,372	3.3	1,714	255
HV2	Town Centre 6.6kV	3,120	3	1,108	105
HV3	Suburban UG 11kV	3,372	6	1,714	276
HV4	Suburban UG 6.6kV	3,120	6	1,108	226
HV5	Mixed 11kV	3,372	14.8	2,020	136
HV6	Mixed/Rural 6.6kV	1,474	14.8	468	18
HV7	Rural OH 11kV	2,114	16.3	1,181	167
HV8	Single Transformer Primary 11kV	2,114	16.3	1,181	87
				Total	1,270

Table 6 **Representative feeders of the LV distribution network in Northern Ireland**

Feeder	Feeder definition	Thermal rating (kVA)	Length (km)	Peak load (kVA)	Number of networks
LV1	Belfast city (Commercial)	162	0.25	143	427
LV2	Dense Urban (apartments etc.)	205	0.2	95	428
LV3	Town Centre	162	0.25	143	3,473
LV4	Industrial estate	205	0.3	180	860
LV5	Retail park	205	0.3	150	851
LV6	Housing pre 1990s (3-4 bed semi-detached and detached)	140	0.3	80	8,617
LV7	New build housing estate	205	0.3	145	3,986
LV8	Terraced street Belfast	140	0.25	110	858
LV9	Single dwelling	18	0.04	8	25,645

Feeder	Feeder definition	Thermal rating (kVA)	Length (km)	Peak load (kVA)	Number of networks
LV10	Large farms	80	0.15	47	4,796
LV11	Rural hamlet	125	0.4	70	2,146
LV12	Generator export	Single generator customer – sized accordingly and no further load connected		-28	300
LV13	Rural 2-3 dwellings	80	0.15	19	21,587
LV14	Other Terraced	205	0.3	70	4,236
LV15	Town Centre (Light)	162	0.25	32	1,612
LV16	Housing pre 1990s (Light)	140	0.3	14	8,562
LV17	Other Terraced (Light)	205	0.3	26	4,246
				Total	92,630

4.2.3 Representative feeder parameterisation

Information pertaining to network topology and intervention thresholds for the different types of headroom and legroom were derived from the information and data provided by NIE Networks and discussed during the workshop phase and are presented in Table 7 and Table 8 for different network voltage levels.

The column fields of Table 7 and Table 8 are briefly defined here to assist the reader by taking as an example the "HV5 Mixed 11kV" feeder.

- **Average capacity rating of upstream transformer:** This represents the average size of one transformer at the next substation up the network. In this case, this would be a transformer at the 33/11kV substation that supplies rural mixed 11kV network and is found to be 12.5MVA.

- **Average number of upstream transformers at the upstream substation**: This is the number of 12.5MVA transformers that would be found, on average, at the upstream 33/11kV substation. In this case, two transformers per substation.

- **Average number of feeders out of the upstream substation:** This represents the number of 11kV feeders that would be supplied from the 33/11kV substation. Note that not all of these feeders are necessarily of the HV5 type, but some are. Here it can be seen that from the substation that would ordinarily supply HV5 type feeders, there are on average a total of 5 11kV feeders supplied from the primary substation.

- **Average number of downstream GMTs along the feeder:** This refers to the individual HV5 feeder and is concerned with the number of 11kV/LV ground mounted distribution substations that are supplied from this feeder under normal operation. Here it is seen that an average of 6 ground mounted distribution substations are supplied from one of these feeders.

- **Average number of downstream feeders per downstream GMT:** Having established that there are 6 downstream GMTs along every one of these HV5 feeders, it is then necessary to state how many LV feeders emanate from each of these 6 distribution substations. Table 7 shows that an average of 3 LV feeders are supplied from each substation. This essentially tells us that each HV5 11kV feeder has 6 x 3 = 18 LV feeders supplied directly from it under normal running conditions.

- **Average number of downstream PMTs along the feeder:** As for the GMTs above, his refers to the individual HV5 feeder and is concerned with the number of 11kV/LV pole mounted distribution substations that are supplied from this feeder under normal operation. Here it is seen that an average of 158 pole mounted distribution substations are supplied from one of these feeders.

- **Average number of downstream feeders per downstream PMT:** Having established that there are 158 downstream PMTs along every one of these HV5 feeders, it is then necessary to state how many LV feeders emanate from each of these 158 distribution substations. Table 7 shows that on average, 1 LV feeder is supplied from each substation. This essentially tells us that each HV5 11kV feeder has 158 LV feeders suppled from pole mounted transformers. When combined with the information from GMTs above (where 18 LV feeders were supplied), it can be derived that each HV5 feeder supplies an average of 18 + 158 = 176 LV feeders under normal running conditions.

- **Thermal circuit intervention threshold:** This represents the percentage of rating that the HV5 circuit is allowed to reach before requiring investment. We know from Table 5 that the rating of an HV5 feeder is 3,372kVA and we discover here that the intervention threshold is 60% meaning that the load can be up to 2,023kVA before reinforcement is required.

- **Thermal substation intervention threshold:** This refers to how heavily loaded the upstream substation can be before the decision is taken to reinforce. Here, we know that there are two 12.5MVA transformers, giving a total substation capacity of 25MVA, but clearly the load would not be allowed to reach this level so as to enable network restoration and the taking of outages. In this case, the intervention threshold is found to be 65% (representing 0.65 x 25MVA = 16.25MVA) meaning that the load on this substation can grow to 16.25MVA before an intervention is required.

- **Upper voltage intervention threshold**: This is how much in percentage terms the voltage can increase from its nominal starting position (as measured at the 11kV circuit breaker) before it will go outside of the voltage limits and will require mitigating action. Here the voltage can rise by 3%.

- **Lower voltage intervention threshold:** This represents how much in percentage terms the voltage can drop from its nominal starting position (as measured at the 11kV circuit breaker) before it will go outside of the voltage limits and will require mitigating action. Here the voltage can drop by up to 6%.

- **Fault level intervention threshold:** This represents the upper limit that the fault level can rise to before a fault level driven reinforcement is necessary. In this example, the maximum allowable fault level is 250MVA.

Table 7 Subset of distribution network feeder parameters

	Upstream substation			Downstream substation			
Feeder	Average capacity rating of upstream transformer (kVA)	Average number of upstream transformers at the upstream substation	Average number of feeders out of the upstream substation	Average number of downstream GMTs along the feeder	Average number of downstream feeders per downstream GMT	Average number of downstream PMTs along the feeder	Average number of downstream feeders per downstream PMT
EHV1 Urban Underground Radial	90,000	2	1	1	9	n/a	n/a
EHV2 Urban Underground Meshed	90,000	2	1	1	9	n/a	n/a
EHV3 Rural Mixed Radial	60,000	2	1	1	4	n/a	n/a
EHV4 Rural Mixed Meshed	60,000	2	1	1	4	n/a	n/a
HV1 Town Centre 11kV	15,000	2	10	9	3	n/a	n/a
HV2 Town Centre 6.6kV	15,000	2	8	6	4	n/a	n/a
HV3 Suburban UG 11kV	12,500	2	6	9	3	n/a	n/a
HV4 Suburban UG 6.6kV	12,500	2	8	6	4	n/a	n/a
HV5 Mixed 11kV	12,500	2	5	6	3	158	1
HV6 Mixed/Rural 6.6kV	10,000	2	5	7	3	17	1
HV7 Rural OH 11kV	5,000	2	4	n/a	n/a	180	1
HV8 Single Transformer Primary 11kV	6,250	1	3	n/a	n/a	180	1
LV1 Belfast city (Commercial)	1,000	1	8	n/a	n/a	n/a	n/a
LV2 Dense Urban (apartments etc)	500	1	5	n/a	n/a	n/a	n/a
LV3 Town Centre	500	1	5	n/a	n/a	n/a	n/a
LV4 Industrial estate	500	1	3	n/a	n/a	n/a	n/a
LV5 Retail park	500	1	6	n/a	n/a	n/a	n/a
LV6 Housing pre 1990s (3-4 bed semi-detached and detached)	500	1	5	n/a	n/a	n/a	n/a
LV7 New build housing estate	315	1	4	n/a	n/a	n/a	n/a
LV8 Terraced street	800	1	7	n/a	n/a	n/a	n/a
LV9 Single dwelling	16	1	1	n/a	n/a	n/a	n/a
LV10 Large farms	50	1	1	n/a	n/a	n/a	n/a
LV11 Rural hamlet	100	1	1	n/a	n/a	n/a	n/a
LV12 Generator export	1000	1	1	n/a	n/a	n/a	n/a
LV13 2-3 dwellings	25	1	1	n/a	n/a	n/a	n/a
LV14 Other terraced	500	1	6	n/a	n/a	n/a	n/a
LV15 Town Centre (Light)	500	1	5	n/a	n/a	n/a	n/a
LV16 Housing pre 1990s (Light)	500	1	5	n/a	n/a	n/a	n/a
LV17 Other Terraced (Light)	500	1	6	n/a	n/a	n/a	n/a

Table 8 Network intervention thresholds for Northern Ireland distribution network

Feeder	Thermal circuit intervention threshold (%)	Thermal substation intervention threshold (%)	Lower voltage intervention threshold (%)	Upper voltage intervention threshold (%)	Fault level intervention threshold (MVA)
EHV1 Urban Underground Radial	50%	50%	6%	4%	750
EHV2 Urban Underground Meshed	60%	50%	6%	4%	750
EHV3 Rural Mixed Radial	50%	50%	6%	4%	750
EHV4 Rural Mixed Meshed	60%	50%	6%	4%	750
HV1 Town Centre 11kV	60%	65%	6%	3%	250
HV2 Town Centre 6.6kV	60%	65%	6%	3%	150
HV3 Suburban UG 11kV	60%	65%	6%	3%	250
HV4 Suburban UG 6.6kV	60%	65%	6%	3%	150
HV5 Mixed 11kV	60%	65%	6%	3%	250
HV6 Mixed/Rural 6.6kV	60%	65%	6%	3%	150
HV7 Rural OH 11kV	60%	65%	6%	3%	250
HV8 Single Transformer Primary 11kV	60%	65%	6%	3%	250
LV1 Belfast city (Commercial)	100%	130%	6%	10%	25
LV2 Dense Urban (apartments etc)	100%	130%	6%	10%	25
LV3 Town Centre	100%	130%	6%	10%	25
LV4 Industrial estate	100%	130%	6%	10%	25
LV5 Retail park	100%	130%	6%	10%	25
LV6 Housing pre 1990s (3-4 bed semi-detached and detached)	100%	130%	6%	10%	25
LV7 New build housing estate	100%	130%	6%	10%	25
LV8 Terraced street	100%	130%	6%	10%	25
LV9 Single dwelling	100%	130%	6%	10%	25
LV10 Large farms	100%	130%	6%	10%	25
LV11 Rural hamlet	100%	130%	6%	10%	25
LV12 Generator export	100%	130%	6%	10%	25
LV13 2-3 dwellings	100%	130%	6%	10%	25
LV14 Other terraced	100%	130%	6%	10%	25
LV15 Town Centre (Light)	100%	130%	6%	10%	25
LV16 Housing pre 1990s (Light)	100%	130%	6%	10%	25
LV17 Other Terraced (Light)	100%	130%	6%	10%	25

4.3 Representative distribution network

The representative feeders of the Northern Ireland distribution network are combined across the different voltage levels existing in the real Northern Ireland distribution network to form a representative network of the entire NIE Networks distribution network. Figure 20 depicts an overview of the three-tiered network that exists within the Transform Model, showing that connections are made between the EHV, HV and LV voltage levels such that the aggregation of loads at the lower voltage levels can be calculated higher up the network, thus allowing examination of the loads that will occur on all feeders at all voltage levels over the modelled period.

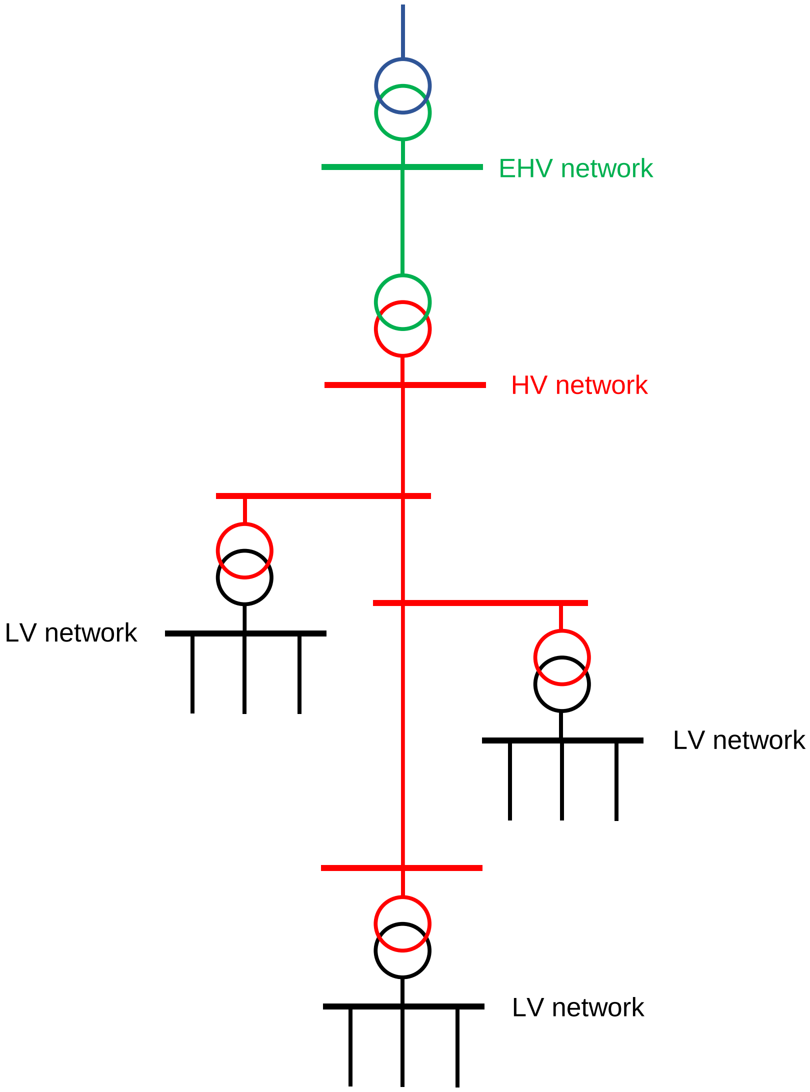

Figure 20 **Schematic diagram of the network**

In order to ensure that the loads can be calculated appropriately, it is important to establish which types of HV feeder are fed from which EHV feeders (and similarly which LV feeders are supplied from which HV feeders). In order to do this, a representation such as that shown in Figure 21 is developed. This allows the various parametric feeders to be combined to constitute a network which is representative of that found in Northern Ireland. Clearly, only certain combinations of feeders are possible (urban underground HV feeders will not supply LV overhead rural farm circuits, for example) and hence this representation does not contain all possible combinations, but only those that are realistic.

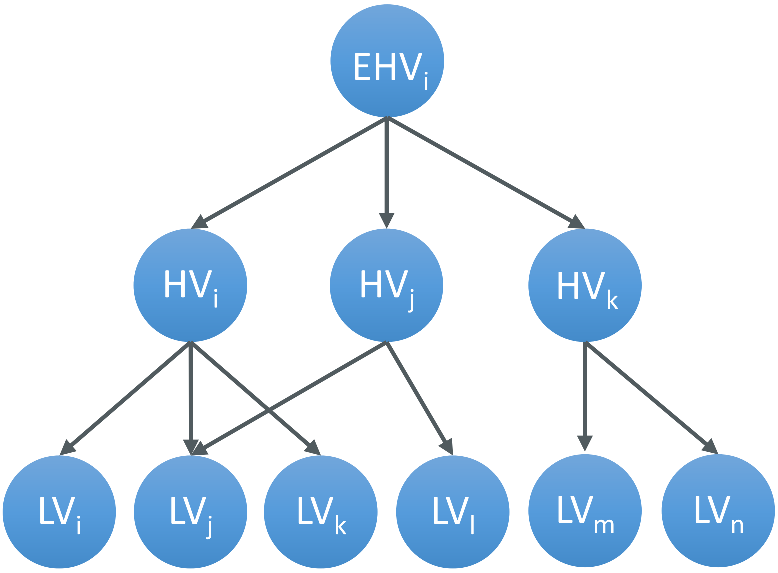

Figure 21 **Combinations of parametric feeders**

Having established the feasible combinations of feeders, they are then apportioned such that an appropriate number of each feeder type is connected to the relevant upstream feeder. This information is then populated within the Transform Model. The following tables demonstrate the likely combinations of feeders, as agreed with NIE Networks at a workshop, which are then populated as feasible links within the modelling environment.

Table 9 **Connections between EHV and HV representative feeders in the Northern Ireland distribution network**

EHV feeder	EHV1	EHV2	EHV3	EHV4
HV feeders supplied by EHV feeder	HV1	HV2	HV1	HV1
	HV3	HV4	HV3	HV4
	HV5	HV6	HV5	HV5
	HV8		HV6	HV6
			HV7	HV7
			HV8	HV8

Table 10 **Connections between HV and LV representative feeders in the Northern Ireland distribution network**

HV feeder	HV1	HV2	HV3	HV4	HV5	HV6	HV7	HV8
LV feeders supplied by HV feeder	LV1	LV1	LV2	LV2	LV7	LV11	LV9	LV9
	LV2	LV2	LV3	LV3	LV9	LV14	LV10	LV16
	LV3	LV3	LV4	LV4	LV11	LV15	LV11	
	LV4	LV4	LV5	LV5	LV13	LV17	LV12	
	LV5	LV5	LV6	LV6	LV14		LV13	
	LV6	LV6	LV7	LV7	LV15		LV16	
	LV7	LV7	LV8	LV8	LV16			
	LV8	LV8	LV14	LV14	LV17			
	LV14	LV14		LV16				

4.4 Feeder and network loads

The electricity demand of each representative feeder is characterised by the half-hour time series of load across representative days. For each year, three representative days are considered, i.e. an average ‘summer’ weekday, an average ‘winter’ weekday and a ‘peak winter’ weekday. The load profiles for the representative feeders were developed from the data provided by NIE Networks for individual customers and feeders that was then scaled appropriately depending on the number of customers connected per feeder type.

The loads obtained for the LV representative feeders were then used to build the loads for the higher voltage feeders (HV and EHV) through the ‘bottom-up’ approach inherent to the Transform Model. This process was then quality assured by ensuring that the shape and magnitude of the network loads calculated by the Transform Model for each of the EHV, HV and LV representative feeders were consistent with the real overall distribution network load in Northern Ireland.

Figure 22 shows the load profile for a winter peak day across the distribution network for the base year (2016), i.e. before the addition of low carbon technologies.

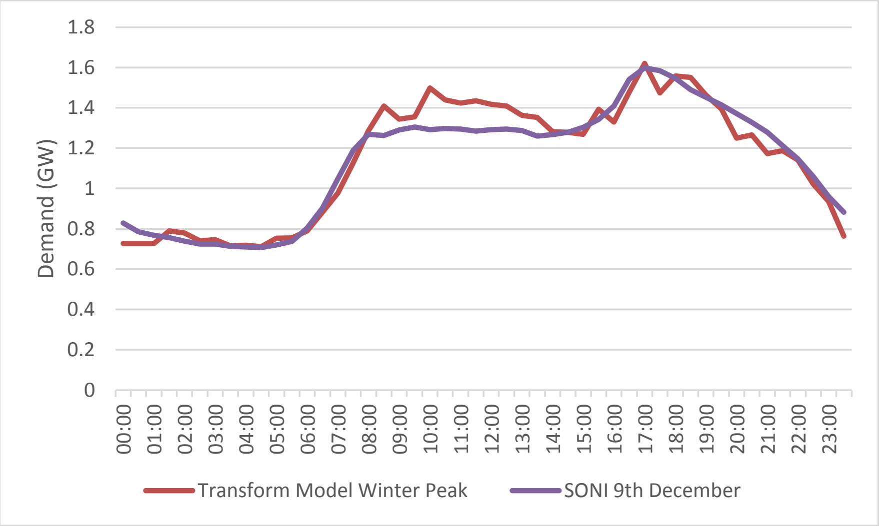

Figure 22 **Demand profile for winter day in 2015 taken from SONI compared with a 2016 winter day in the Transform Model**

5. Engineering Solutions

Networks are made up of a range of technologies that are applied in different combinations and at different geographical scale to enable the transfer of energy from grid exit points to consumer load points. The increasing presence of low carbon technologies in distribution networks will cause thermal, voltage or fault level headroom (or voltage legroom) limits to change over time. The reduction of headroom levels to a pre-set limit will require the DNO to intervene in the network in order to release headroom ensuring security and quality of supply. The engineering solutions/technologies deployed by the Transform Model to resolve network constraint problems can be divided in two different categories:

- **Conventional solutions**: This refers to technological network solutions that are widely used in the design, operation and management of the current networks. Examples of conventional solutions include traditional reinforcement options such as laying new cables, replacing transformers, etc.

- **Smart solutions**: This refers to new technological and/or commercial solutions that, in most cases, have not yet been widely deployed. Even technologies which are well understood, and have been trialled are considered to be smart in this framework, since they have not yet been widely deployed. These solutions can be operating on the network-side, generation-side or customer-side of the distribution system. Examples of smart solutions include dynamic network reconfiguration, dynamic thermal ratings, enhanced automatic voltage control, etc.

The Transform Model selects the most appropriate solution set (i.e. smart and/or conventional) for each required intervention across the network that enable the cost-efficient and secure integration of low carbon technologies in the Northern Ireland electricity network.

5.1 Smart solutions

Smart solutions refer to new technological and/or commercial solutions that, in most cases, have not yet been widely deployed. Even technologies that are well understood, and have been trialled are considered to be smart in this framework, since they have not yet been widely deployed. These solutions can be operating on the network-side, generation-side or customer-side of the distribution system. The smart solution sets included in the Transform Model for the development of smart grids are presented in Table 11.

It is important to note that all solutions are ascribed a year in which they become ‘available’. This indicates that the solution has reached a sufficient degree of maturity that it can be deployed in an off-the-shelf manner by NIE Networks. These years of availability were defined at a workshop with NIE Networks and represent the fact that further work is required to fully integrate these solutions into business as usual practice before they can be deployed. Hence for the initial modelled period (up to around 2020), available solutions are restricted to the conventional or well-understood smart solutions.

Table 11 **Smart solutions**

Representative solution	Description	Variants
Active Network Management - Dynamic Network Reconfiguration	The pro-active movement of network split (or open) points to align with the null loading points within the network.	☐EHV
		☐HV
		☐LV
Distribution Flexible AC Transmission Systems (D-FACTS)	Series or shunt connected static power electronics as a means to enhance controllability and increase power transfer capability of a network.	☐STATCOM - EHV
		☐STATCOM - HV
		☐STATCOM - LV
		☐Basic D-FACTS - EHV
		☐Basic D-FACTS - HV
		☐Basic D-FACTS - LV
Demand Side Response (DSR)	The signalling to demand side customers to move load at certain times of day. It is applicable to a broad range of customers, and giving benefits to different network voltages – hence the large number of variants.	☐DNO to residential
		☐DNO to aggregator led EHV connected commercial DSR
		☐DNO to EHV commercial DSR
		☐DNO to Central Business District DSR
		☐DNO to EHV connected commercial DSR
		☐DNO to HV commercial DSR
Electrical Energy Storage	Electrical Energy Storage, e.g. large battery units, for voltage support and load shifting. Storage comes in all shapes and sizes, but the DNO is largely agnostic to the technology used. As the costs are currently expensive, several sizes of storage units have been included as variants.	☐HV Central Business District (commercial building level)
		☐EHV connected EES - large
		☐EHV connected EES - medium
		☐EHV connected EES - small
		☐HV connected EES - large
		☐HV connected EES - medium
		☐HV connected EES - small
		☐LV connected EES - large
		☐LV connected EES - medium
		☐LV connected EES - small
Embedded DC networks	The application of point-to-point DC circuits to feed specific loads (used in a similar manner to transmission 'HVDC', but for distribution voltages). A retrofit solution to existing circuits.	☐EHV
		☐HV
		☐LV
Enhanced Automatic Voltage Control	A refinement to conventional automatic voltage control solutions (traditionally applied as far as the Primary busbars); with additional voltage control down the HV circuits and up to the customer cut-out in a dwelling.	☐EHV circuit voltage regulators
		☐HV circuit voltage regulators
		☐HV/LV Transformer voltage control
		☐LV circuit voltage regulators
		☐LV point of connection voltage regulators
Fault Current Limiters	Devices to clamp fault current at time of fault, in order to maintain operation within the limits of switchgear.	☐EHV Non-superconducting fault current limiters
		☐EHV Superconducting fault current limiters
		☐HV Superconducting fault current limiters
		☐HV Non-superconducting fault current limiters
		☐HV reactors - middle circuit
Generation Constraint Management	The signalling to generators to ramp down output at certain times of the year, or under certain loading/outage conditions.	☐EHV connected
		☐HV connected
		☐LV connected
Generator Providing Network Support	Operation of a generator in PV (power and voltage) mode to support network voltage through producing or absorbing reactive power (VArs)	☐EHV connected
		☐HV connected
		☐LV connected
Local intelligent EV charging control	An EV charging solution applied by the DNO to apportion capacity to several EVs on a feeder across a charging cycle.	☐LV domestic connected
New Types Of Circuit Infrastructure	New types of overhead lines or underground cables. It is assumed that these circuit types will have a larger capacity than conventional circuits owing to improvements in current carrying capability.	☐Novel EHV tower and insulator structures
		☐Novel EHV underground cable
		☐Novel HV tower and insulator structures
		☐Novel HV underground cable
Permanent Meshing of Networks	Converting the operation of the network from a radial ring (with split points) to a solid mesh configuration.	☐EHV
		☐HV
		☐LV urban
		☐LV suburban
Real Time Thermal Rating	Increases to circuit or asset rating through the use of real-time ambient temperature changes and local weather conditions.	☐RTTR for EHV overhead lines
		☐RTTR for EHV underground cables
		☐RTTR for EHV/HV transformers
		☐RTTR for HV overhead lines
		☐RTTR for HV underground cables
		☐RTTR for HV/LV transformers
		☐RTTR for LV overhead lines
		☐RTTR for LV underground cables
Switched Capacitors	Mechanically switched devices as a form of reactive power compensation. They are used for voltage control and network stabilisation under heavy load conditions.	☐EHV
		☐HV
		☐LV
Temporary Meshing (soft open point)	"Temporary meshing" refers to running the network solid, utilising latent capacity, and relying on the use of automation to restore the network following a fault.	☐EHV
		☐HV
		☐LV
Microgrid (islanded LV network)	Islanded LV network for upstream capacity release. It is assumed that the LV network will be able to cope with demand with distributed generation. The solution has been costed appropriately for this to take place.	☐This solution is applied at HV only

Presently, the costs of smart solutions are extracted from the best available information based on real-world field trials and deployment in Great Britain. It should be highlighted that the present smart solution sets will be improved over time as new information regarding costs, benefits and functionalities become available. Furthermore, different feasible future solutions can be added as appropriate.

5.2 Solution enabling technologies

'Enablers' refer to components that are part of a solution and that are not able to provide headroom benefits when deployed on their own. Enablers are typically associated with monitoring, communications or control systems. For example, a real time thermal ratings (RTTR) system requires communications, load monitoring and ambient temperature sensors to allow the real time rating algorithms to function. These three enabling technologies cannot, in isolation, provide a real time ratings system, and hence individually they release no headroom. For instance, the algorithms cannot perform their function without these technologies working together. Enablers have the potential to be provided separately from the Solution itself, for example a communications infrastructure could be laid down in advance and utilised for more than one Solution application. The enabler sets included in the Transform Model for the development of smart grids are presented in Table 12.

Table 12 Enabling technologies

Enabler	Description
Advanced control systems	System to intelligently control remote equipment.
Communications to and from devices – Last mile only	Communications which support remote devices such as RTTR
Design tools	New design tools and software with enhanced capabilities (i.e. the inclusion of EES).
DSR - Products to remotely control loads at consumer premises	Communications and device to enable DNO-initiated DSR
DSR - Products to remotely control EV charging	Devices to enable control of charging of EVs
EHV Circuit Monitoring	Monitoring of power flow and voltage on EHV circuits (e.g. used for RTTR)
HV Circuit Monitoring (along feeder)	Monitoring of power flow and voltage on HV circuits (e.g. used for RTTR)
HV Circuit Monitoring (along feeder) w/ State Estimation	Simplified monitoring of power flow and voltage relying on state estimation
EHV/HV Transformer Monitoring	Monitoring of power flow and voltage at primary transformers
HV Circuit Monitoring (along feeder) w/ State Estimation	Simplified monitoring of power flow and voltage relying on state estimation
HV/LV Transformer Monitoring	Monitoring of power flow and voltage at distribution transformers
HV Circuit Monitoring (along feeder)	Monitoring of power flow and voltage on HV circuits (e.g. used for RTTR)
Link boxes fitted with remote control	Communications and control to enable the remote switching of link boxes for temporary meshing solutions
LV Circuit Monitoring (along feeder)	Monitoring of power flow and voltage on LV circuits (e.g. used for RTTR)
LV Circuit monitoring (along feeder) w/ state estimation	Simplified monitoring of power flow and voltage relying on state estimation
LV feeder monitoring at distribution substation	Measurement devices and appropriate communications to allow the LV loads per circuit at the substation to be monitored
LV feeder monitoring at distribution substation w/ state estimation	Simplified version of measurement devices and appropriate communications to allow the LV loads per circuit at the substation to be monitored, based on state estimation
RMUs Fitted with Actuators	HV switchgear that is remotely controllable to allow dynamic network reconfiguration
Communications to DSR aggregator	Communications links to aggregators for aggregator-led DSR
Dynamic Network Protection, 11kV	Network protection to support solutions such as temporary meshing
Weather monitoring	Weather monitoring stations with localised communications for use in RTTR
Monitoring waveform quality (EHV/HV Transformer)	Power quality measurement devices at primary transformers
Monitoring waveform quality (EHV/HV Transformer)	Power quality measurement devices at primary transformers
Monitoring waveform quality (EHV feeder)	Power quality measurement devices along an EHV circuit
Monitoring waveform quality (HV Feeder)	Power quality measurement devices along an HV circuit
Monitoring waveform quality (HV/LV Transformer)	Power quality measurement devices at distribution transformers
Monitoring waveform quality (LV Feeder)	Power quality measurement devices along an LV circuit
Smart Metering infrastructure - smart meter data provider to DNO 1 way	Communications necessary to allow one-way data flow with the smart meter data provider
Smart Metering infrastructure - DNO to smart meter data provider 2 way A+D	Communications necessary to allow two-way analogue and digital data flow with the smart meter data provider
Smart Metering infrastructure - DNO to smart meter data provider 2 way control	Communications necessary to allow two-way commands and control to be passed between the DNO and the smart meter data provider
Phase imbalance - EHV circuit	Monitoring devices to determine phase imbalance along an EHV feeder to establish the level of de-rating being caused through imbalance
Phase imbalance - HV circuit	Monitoring devices to determine phase imbalance along an HV feeder to establish the level of de-rating being caused through imbalance
Phase imbalance - LV distribution s/s	Monitoring devices to determine phase imbalance at distribution substations to establish the level of de-rating being caused through imbalance
Phase imbalance - LV circuit	Monitoring devices to determine phase imbalance along an LV feeder to establish the level of de-rating being caused through imbalance
Phase imbalance - smart meter phase identification	Using smart meters to identify the phase of connection of customers and therefore determine the phase imbalance along a feeder
Phase imbalance - LV connect customer, 3 phase	Monitoring device to determine the degree to which a three phase customer’s load is balanced

5.3 Conventional solutions

Conventional solutions refer to technological network solutions that are widely used in the design, operation and management of today’s distribution networks such as traditional reinforcement options. The future network will be made up of a combination of both conventional and smart solutions; however conventional solutions will be favoured to smart in the Transform Model if they constitute a more efficient investment. The conventional solution sets included in the Transform Model for the development of smart grids are presented in Table 13. A detailed description of each conventional solution set is provided in Appendix II.

Table 13 **Conventional solutions**

Representative solution	Description	Variants
Split feeder	Transfer half of the load of the existing feeder onto a new feeder.	□EHV
		□HV
		□LV
New split feeder	Run a new feeder from the substation to the midpoint of the already split feeder and perform some cable jointing to further split the load, resulting in three feeders each having approximately equal loads.	□EHV
		□HV
		□LV
Replace transformer	New transformer, providing additional capacity and voltage support.	□HV (EHV/HV)
		□LV (HV/LV)
Minor works	The construction of one complete new substation electrically adjacent to an area experiencing headroom constraints.	□EHV
		□HV
		□LV
Major works	The construction of new distribution transformers and circuits into an area where demand cannot be satisfied by simply ‘tweaking’ existing network infrastructure.	□EHV
		□HV
		□LV

The costs of the conventional solutions have been set to be the same value as the costs used in the Great Britain implementation of the Transform Model as a default.

5.4 Framework for the deployment of distribution network solutions

The presence of low carbon technologies in distribution networks will cause thermal, voltage or fault level headroom (or voltage legroom) limits to change over time. The reduction of headroom levels to a pre-set trigger limit will require the DNO to intervene in the network in order to release headroom ensuring security and quality of supply. In this respect, the Transform Model seeks to select and deploy smart and conventional solutions to resolve network constraint problems through a variable ‘merit order stack’. The merit of each network solution is characterised by a ‘cost function’ of the following elements:

- **TOTEX**: the sum of capital expenditure (CAPEX) plus the net present value (NPV) of annual operating expenditure (OPEX[16]) over the life of the asset
- **Disruption**: the value placed on avoiding the disruption required to install and operate a solution. This is converted from a 1-5 scale into a currency value.
- **Cross network benefits**: the ability for a solution to deliver benefits to an adjacent network (e.g. a HV solution that also gives a benefit to EHV network or LV network). This is converted from a 1-5 scale into a currency value.
- **Flexibility**: the ability to relocate/reuse a solution when it has fulfilled its primary purpose. This takes into account the asset life expectancy and any ancillary benefits offered by the

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[16] It is important to note that while OPEX does include well-established costs (such as those associated with maintenance), it also allows for other costs associated with smart solutions, such as the rental of communications channels. However it does not include indirect opex costs such as those associated with design, project management, back-office etc.

solution. This is converted from a 1-5 scale into multiplication factor (currently set from 0.8x for high flexibility solutions to 1.0x for low flexibility solutions).

- **Life expectancy**: this considers the residual life of the asset at point *n* in time (where *n* is set to be the number of years forward in time for the model to resolve a problem, following a breach of headroom)

These elements are then combined to obtain the merit cost of a particular solution as follows:

$$Solution\ Merit\ Cost = Flexibility \times \left(\frac{n}{Life\ Expectancy}\right) \times (TOTEX + Disruption + Cross\ Networks\ Benefits)$$

It should be noted that the 'solution merit cost' is different from the cost of the solution (i.e. TOTEX) and it is only used for the purposes of ranking different solutions against each other in a comprehensive and consistent manner.

Figure 23 illustrates the merit order stack for network solutions. The merit order stack is arranged with the cheapest solutions at the top of the stack (i.e. low merit order cost) and the most expensive at the bottom of the stack (i.e. high merit order cost).

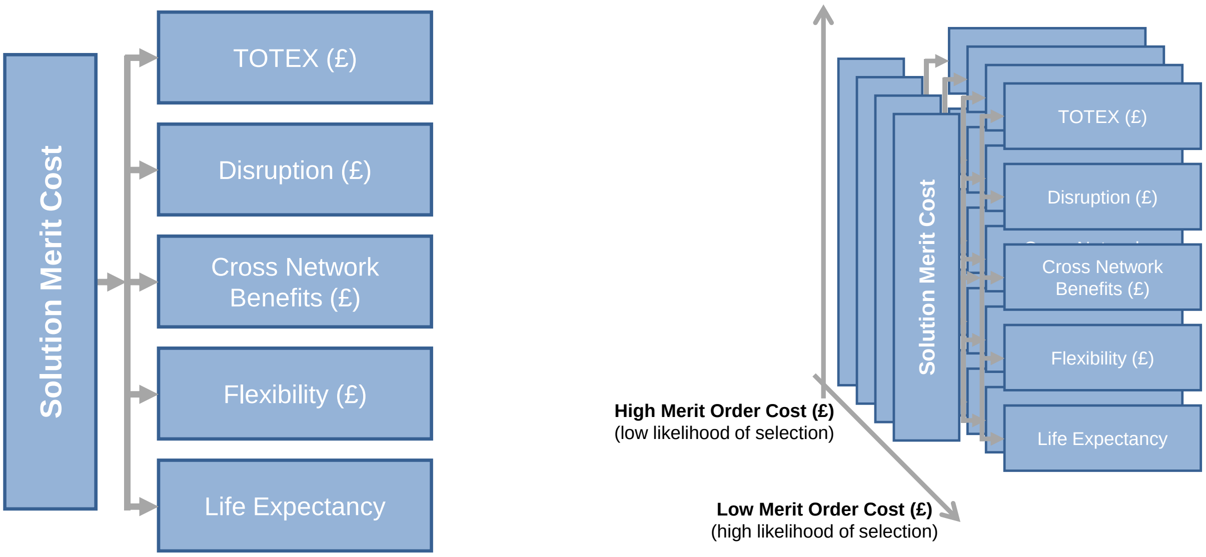

Figure 23 **Merit order stack for network solutions**

The Transform Model initially selects the single least cost solution from the merit order stack to mitigate a network constraint (i.e. headroom/legroom issue). In case the network constraint still persists, the model proceeds to find the least cost combination of two solutions that solves the network constraint otherwise it repeats the process for a combination of up to three solutions in a particular year. The approach credits solutions that are deployed to resolve one network constraint type (e.g. voltage legroom) that has an impact on other network constraint types (e.g. the solution deployed to resolve a voltage legroom violation may also increase thermal headroom). This framework is consistently applied for both smart and conventional solutions.

An example of this calculation is given in Appendix IV.

6. Impact Assessment of LCTs on Northern Ireland's Electricity Distribution Network

This section provides a comprehensive understanding of the impacts associated with the integration of low carbon technologies in the Northern Ireland electricity distribution network. Particularly, this section uses the Transform Model to assess strategic investment planning decisions in the distribution network and to quantify and assess the effects of low carbon technologies on the planning and development of the distribution network within Northern Ireland.

The analyses will assist NIE Networks (and other stakeholders) to accomplish an effective decision making process in respect to strategic smart distribution grid planning and development by addressing the following questions:

- How much future distribution network investment is required to integrate low carbon technologies in a technical and economically efficient manner?
- What is the level of uncertainty surrounding future distribution network investment?
- What are the key drivers prompting expenditure for future network development, their impact and magnitude?
- Where is the future distribution network investment located?
- What engineering solutions (i.e. conventional and/or smart) to deploy in the future distribution network to efficiently integrate low carbon technologies?

6.1 Distribution network investment profile

6.1.1 Low carbon technology related expenditure levels

The Transform Model was applied to the three scenarios that were previously described in Section 3 which describe potential future growth of low carbon technologies within Northern Ireland. The varying uptake levels of low carbon technologies are referred to here as "Low", "Central" and "High". Each is assessed to quantify the levels of network investment required to accommodate such technologies under a range of conventional and smart investment strategies (as defined in section 2.2).

The distribution network investment is presented in terms of discounted totex, or net present value (NPV), of the expenditure required for network development over a future time period. This network expenditure totex is composed of capital and operational expenditures (i.e. capex and opex respectively). In the context of the Transform Model, capex relates to costs incurred in acquiring, preparing and deploying network assets and opex relates to costs sustained to operate, maintain and repair network assets over their life period. The totex of an investment is calculated by adding the capex requirement to the NPV of the opex over the life of the asset.

The analysis covers the period from 2016 to 2060 where the year 2016 is considered to be the economic reference year. For the purpose of this discussion, the discount rate used in the NPV calculation of future network expenditure streams is the social time preference rate (STPR), which is commonly applied when forecasting over longer time periods. This equates to 3.5% up to 2045, and 3% beyond 2045. It should be noted that any discount rate can be used when executing the model.

Figure 24 presents the overall levels of expenditure for distribution network investment that are required to enable the cost-efficient and secure integration of low carbon technologies under different scenarios and investment strategies, for the period 2016 – 2060.

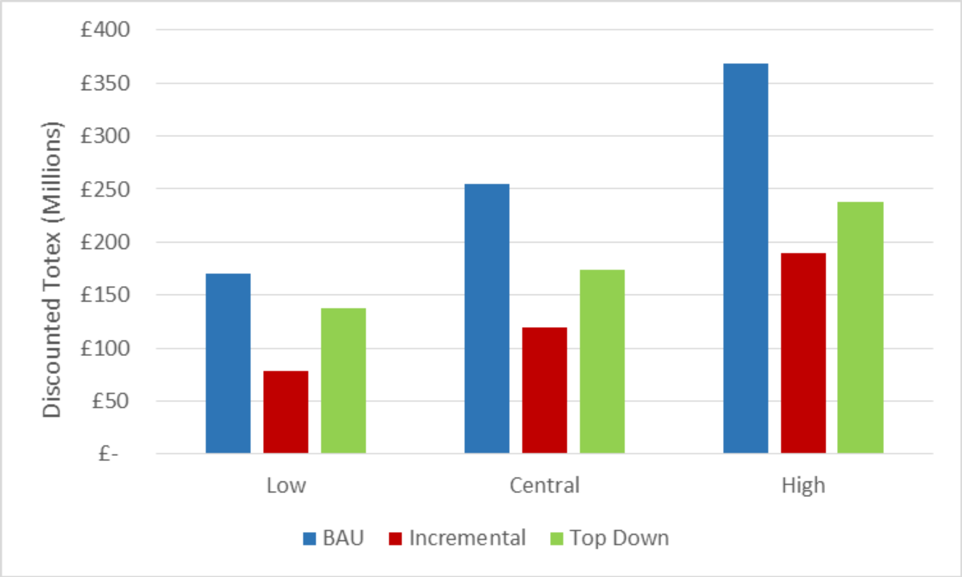

Figure 24 **Distribution network investment – discounted totex over the period 2016 to 2060 for different uptake levels and investment strategies**

It can be seen in Figure 24 that the deployment and integration of low carbon technologies in distribution networks has a significant impact on the levels of expenditure required for the development of distribution grid infrastructure. Grid expenditure is observed to grow with the increasing roll out of such technologies from the lowest to the highest uptake scenario. This demonstrates the critical importance that should be attached to understanding the effects of low carbon technologies on the profile of future expenditure for investment in distribution network assets supporting effective decision making, business planning and risk management.

Opting for a conventional investment strategy, for the planning and development of distribution networks, that relies on traditional grid reinforcement options leads to relatively significant levels of expenditure to efficiently (i.e. technically and economically) integrate low carbon technologies. The overall future distribution network investment in network assets is estimated to increase from approximately £170m in the "Low" scenario to £370m in the "High" scenario in the period 2016 – 2060.

In contrast, adopting a smart incremental strategy to distribution network investment supported by the deployment of both smart and conventional grid technologies could result in considerably lower levels of distribution network investment relating to the growth in uptake of low carbon technologies. The overall future distribution grid expenditure is projected to increase from £78m in the "Low" scenario to £190m in the "High" scenario in the period 2016 – 2060. It is important to note that this represents a situation where all smart grid solutions are available to NIE Networks from the year in which it was felt they could reasonably be ready for mass deployment. It should be stressed that in order for this to be the case, significant research, development and business integration of these solutions would be necessary to facilitate this level of overall investment in the future.

The smart top-down strategy for grid development proposes an initial investment in control and communication infrastructure to support the deployment of smart grid solutions in the future. It can be observed in Figure 24 that favouring this strategy to a smart incremental approach is less cost-effective. The reason for this is that the uptake levels of low carbon technologies are not sufficiently high, particularly in the early years of the modelled period, to justify this outlay and to recoup the savings that will accrue through not having to deploy enablers with solutions going forward.

The difference in investment requirements to facilitate a top-down strategy as opposed to an incremental approach is seen to be broadly consistent across the three scenarios, although as the penetration of LCTs increases (in the high scenario) the differential between the two is reduced (£48m as opposed to £59m in the low scenario). This is to be expected as a higher uptake favours this strategic approach. However, the total investment allowing for the up-front deployment of monitoring technologies, followed by an approach of selecting the most economically efficient solution to resolve network constraints (whether that be a conventional or smart intervention) is less cost-effective than the incremental strategy and hence is not the favoured approach in this case.

The remainder of the results analysis within this report will focus on the conventional and smart incremental investment strategies.

6.1.2 Timing of low carbon technology related investment

While the previous analysis looked at the total expenditure in NPV terms across the period 2015 – 2060, it is also important to analyse the investment profile so as to determine the times at which investment is required. For example, it is clearly important to know whether the profile is significantly front-end or back-end loaded and also to identify any particular 'spikes' in investment. Such spikes are more difficult to manage as they require greater resources in terms of personnel as well as financial, whereas a smooth investment profile is easier to deploy.

To facilitate this analysis, the following graph, Figure 25, focuses on seven-year windows to align with the timescales that are usually considered as part of a regulatory cycle.

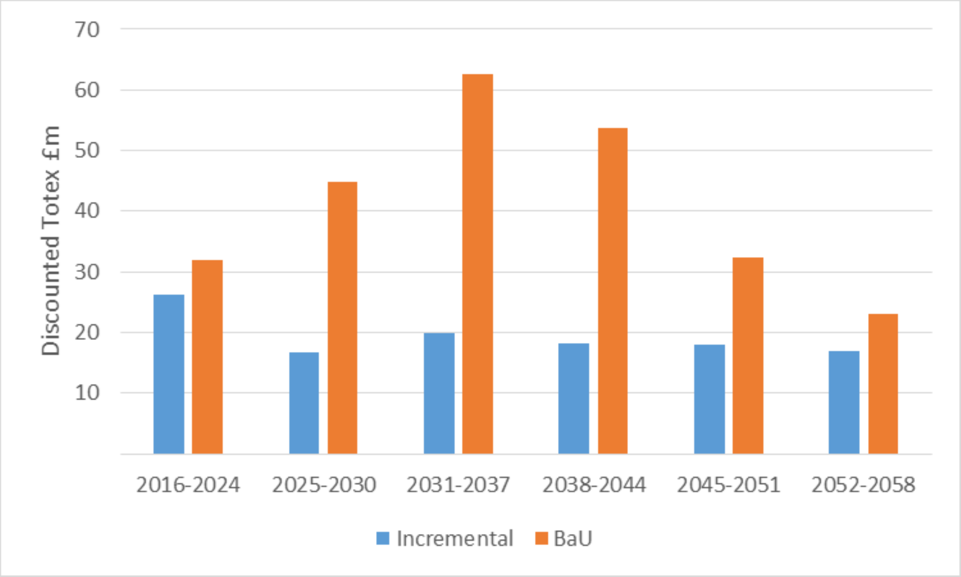

Figure 25 **Distribution network investment split by time periods for central scenario**

It can be seen that in the first time period (until the end of RP6), the investment levels are broadly similar irrespective of strategy. This is because the number of smart solutions available for business as usual implementation is low, and consequently the solutions deployed are of a conventional nature. As we move forward, the investment increases sharply in the second period if a conventional approach is adopted, but is reduced in the event of a smart incremental strategy being utilised. During the 2030s, the amount of investment required in the incremental strategy can be observed to be much lower than the conventional counterpart, demonstrating the value of having the various smart solutions ready to deploy by the mid-2020s so as to maximise these potential savings.

Indeed, in the three periods following RP6, it can be seen that investment is always lower than £20m when adopting the incremental strategy, but in the business as usual approach, the investment varies between £45m and £62m. The reason for this saving is that the uptake scenarios are not hugely aggressive, meaning that it is possible to accommodate the new low carbon technologies through the use of solutions which do not deliver major step changes in headroom (in the way that new transformers or circuits do). Rather, it is possible to manage the demand via the deployment of smaller headroom gain solutions and then to further intervene once the load rises more significantly later in the modelled period.

Later in the modelled period, the difference between the strategies begins to equalise and this is due in part to the fact that the majority of investment in the BAU strategy has been performed earlier, giving large headroom gains from the installation of assets and hence fewer interventions are required in the late 2040s and beyond. In the incremental strategy, a consistent level of incremental investments are made giving more marginal capacity increases, which are still shown to be lower in cost than their conventional counterparts.

A further advantage of such an approach is that it affords a degree of 'optionality'. This means that it is possible for NIE Networks to deploy a lower cost solution that will adequately serve for a number of years while the load change can then be monitored. If the uptake of low carbon technologies accelerates then there will be a need to intervene again in future, but if, in certain areas, it remains fairly static, then there may not be a need to ultimately invest in new assets. This is not a course of action open in the 'conventional' investment strategy where a headroom breach triggers some asset deployment even if the load may then remain flat for many years in the future.

The analysis thus far has considered discounted totex costs (i.e. the NPV of the necessary expenditure), but it can also be helpful to view the gross costs (i.e. the 'cash out of the door' that would need to be spent in a given year. To this end, the following figure (Figure 26) shows the annual gross expenditure required for network development in response to low carbon technologies over the period 2016 – 2060. This expenditure is split into a capex element and an opex element and is illustrated for the smart incremental strategy applied to the central uptake scenario. These charts are provided for each of the uptake scenarios: central, high and low where the smart incremental investment strategy is deployed.

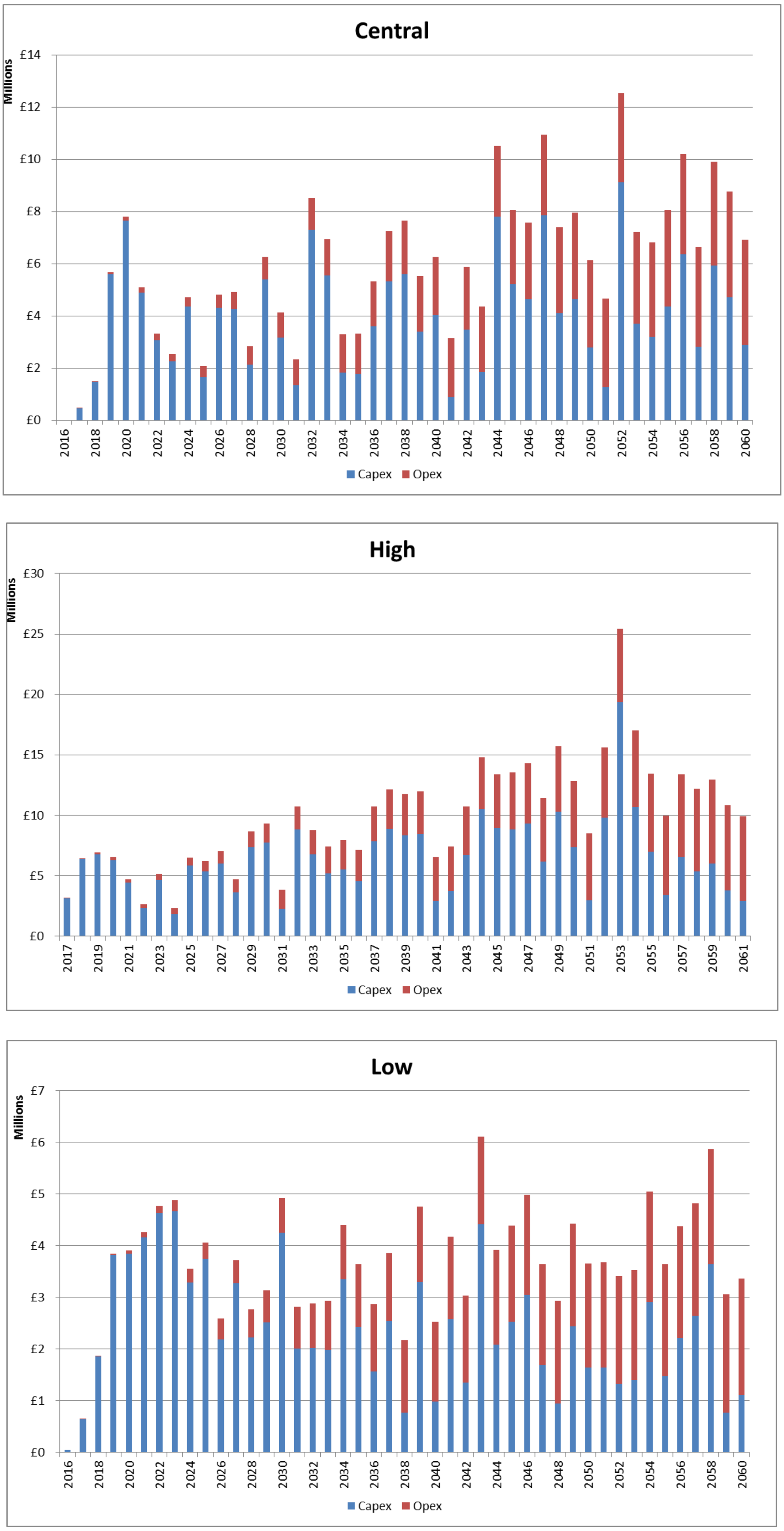

Figure 26 Distribution network investment profile 2016 - 2050 required to accommodate low carbon technologies for various uptake scenarios (smart incremental investment strategy)

Figure 26 illustrates that for the central scenario, the average annual investment required in the early part of the modelled period (2017 – 2030), is approximately £3.6m in capex while the annual opex spend increases from less than £20k to over £900k during the same period (an average of around £380k). After this time, the investment levels tend to increase as a result of the latent spare capacity that exists in the network being eroded through increased penetration of electric vehicles and heat pumps. It should be noted that for the high and low scenarios, the average annual capex over the same time period is approximately £5.1m and £2.9m respectively while the annual opex varies between £271k and £600k.

The annual expenditure levels later in the period (2030s and 2040s) are greater than those in the early period. This highlights the importance of ensuring that the various solutions that are to be deployed to meet this increase in demand are fully available and integrated into business as usual by the time the investment level starts to increase. If all the solutions selected are not available, clearly the costs to accommodate the low carbon technologies will be higher than those indicated here. There is, therefore, a need to ensure that NIE Networks is prepared for this changing environment by developing a targeted innovation plan, exploring solid technological business cases, deploying technological pilots and turning these pilots into reality within business as usual.

Figure 26 further suggests that the capital expenditure required for acquiring, preparing and deploying network assets considerably dominates over the operational expenditure necessary to operate, maintain and repair network assets over their life period. The magnitude of the operational expenditure remains relatively low early in the period and then grows to considerably higher levels as the network deployment of engineering solutions rises to accommodate higher uptakes of low carbon technologies. Moreover, there is a cumulative effect contributing to the overall operational expenditure caused by the fact that the lifetime of different network assets overlaps over time during the period of analysis.

6.2 Distribution network investment uncertainty

Identifying the level of uncertainty surrounding future distribution network investment is critically important in the strategic decision making process for tailoring the network planning and development strategy to that uncertainty and managing risk. The uncertainty framework adopted uses the set of representative future scenarios for the uptake of low carbon technologies, to describe a range of potential future distribution network investment outcomes. Similarly, uncertainty associated with network investment strategies deployed for long-term network development is also assessed. Figure 27 introduces the range of uncertainty related to distribution network investment requirements under different future energy outlooks for the period 2016 – 2060. The figures presented are the gross cumulative (i.e. non-discounted) figures, meaning that the cumulative distribution network expenditure for a particular year in the future corresponds to the sum of the expenditures over the period of time from the beginning of the period of analysis until that year.

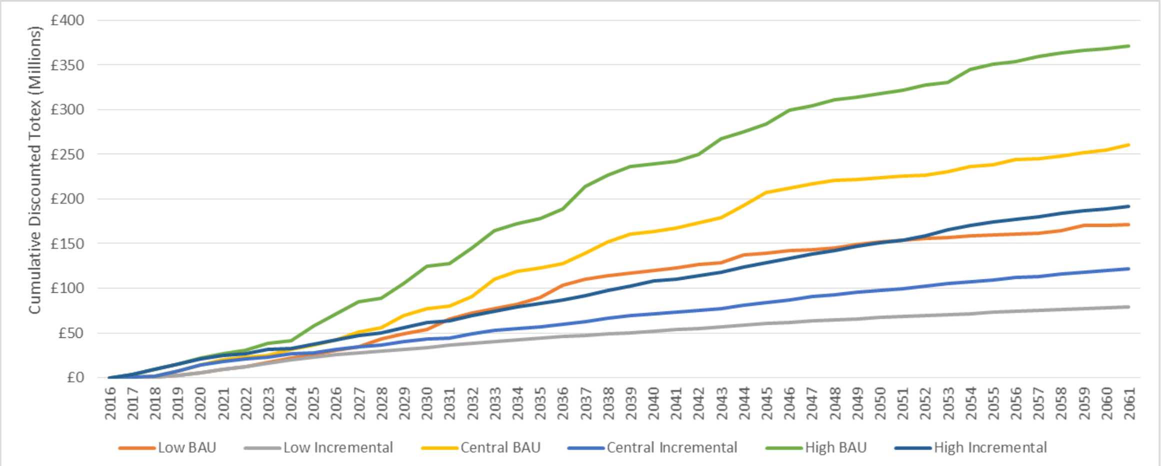

Figure 27 Distribution network investment uncertainty

Figure 27 suggests the range of uncertainty related to expenditure requirements for distribution network development is fairly narrow until the mid-2020s, beyond which it starts to diverge significantly and can become relatively wide depending on the future energy outlook and the strategic approach deployed to long-term grid development. In essence, Figure 27 details that, by 2060, the overall amount spent on mitigating low carbon technology impacts can range from just under £80m to more than £370m depending on the uptake rate of low carbon technologies and the investment strategy selected over the period 2016 – 2060. The magnitude and implications of the uncertainty associated with future distribution network investment are explored in further detail below.

The magnitude of uncertainty in distribution network investment linked to the implementation of a conventional investment strategy is depicted in Figure 28 for the three future energy outlooks during the 2016 – 2060 period of analysis.

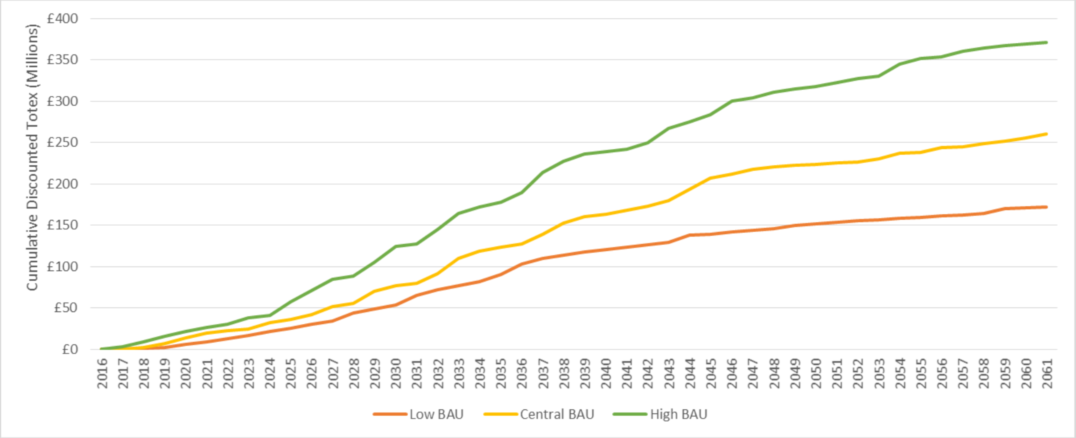

Figure 28 Distribution network investment uncertainty under conventional investment strategy

Figure 28 indicates that overall network expenditure for investment in network assets begins to increase significantly in the early 2020s in all scenarios. Different growth trajectories of low carbon technologies in distribution networks cause the network expenditure profile to diverge somewhat from around 2025 onwards, although all follow a similar trajectory. As a consequence, the range of uncertainty on network expenditure requirements is evaluated to be almost £200m by the end of the year 2060 between the “Low” and the “High” scenario.

The uncertainty related to distribution network investment based on a long-term smart investment strategy is described in Figure 29 for all scenarios over the 2016 – 2060 period.

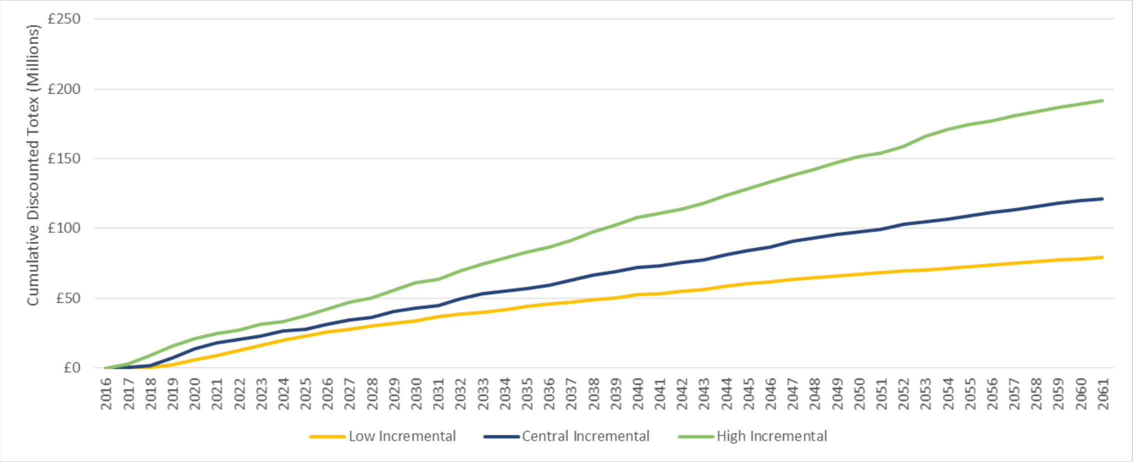

Figure 29 **Distribution network investment uncertainty under smart incremental investment strategy**

Figure 29 shows that the magnitude of uncertainty originating from the adoption of a strategic smart incremental approach to investment is lower than that observed in Figure 28 for a conventional investment strategy. Consequently, under the same growth trajectories for low carbon technologies, it can be seen that the divergence in the network expenditure profiles across the three future energy outlooks is somewhat narrower. This is commensurate with the lower investment levels seen under this investment strategy. Hence, the magnitude of uncertainty in future distribution network expenditure is estimated to be approximately £110m at 2060.

Given that over the first 5 years of the modelled period, almost exclusively conventional solutions are being deployed, the initial trajectories are consistent with the conventional strategy described earlier. As for the conventional strategy, divergence between the investment levels for different uptake scenarios begins in the early 2020s, but while this divergence accelerates in the later 2020s under the conventional strategy, it remains fairly static in the smart incremental strategy. This illustrates that the adoption of a smart investment strategy makes it easier to respond should there be a significant step change in uptake of low carbon technologies in the future. For example, if an incentive were introduced which rapidly transitioned the uptake of electric vehicles from the “low” to the “high” trajectory, the amount of expenditure required to respond to this in a smart investment strategy is considerably lower than that in the conventional strategy. This clearly demonstrates that adopting a smart strategy increases the flexibility for managing risk.

6.3 Distribution network investment drivers

Following the assessment of future distribution network expenditure needs to accommodate the increasing customer uptake of low carbon technologies, the key drivers for network investment are identified and their impact measured as the magnitude of expenditure per driver is quantified.

The growing presence of low carbon technologies (as well as any organic growth in demand) may lead to a reduction in headroom on network assets prompting some form of reinforcement to be undertaken. In these instances, the Transform Model deploys the most economically efficient set of network solutions (i.e. conventional and/or smart) to increase the available headroom to adequate levels. In the Transform Model, distribution network investment decisions are based on three distinct types of headroom, i.e. thermal headroom, voltage headroom and legroom and fault level headroom. This differentiation enables the classification of the drivers for triggering network investment to be established in accordance with the network headroom problem caused by the introduction of low carbon technologies. Expressly, network investment can be driven by thermal problems relating to overloaded feeders or transformers, voltage excursion problems relating to voltage drop or rise or fault level problems.

Figure 30 demonstrates the proportion of total (undiscounted) network investment driven by each of these constraints.

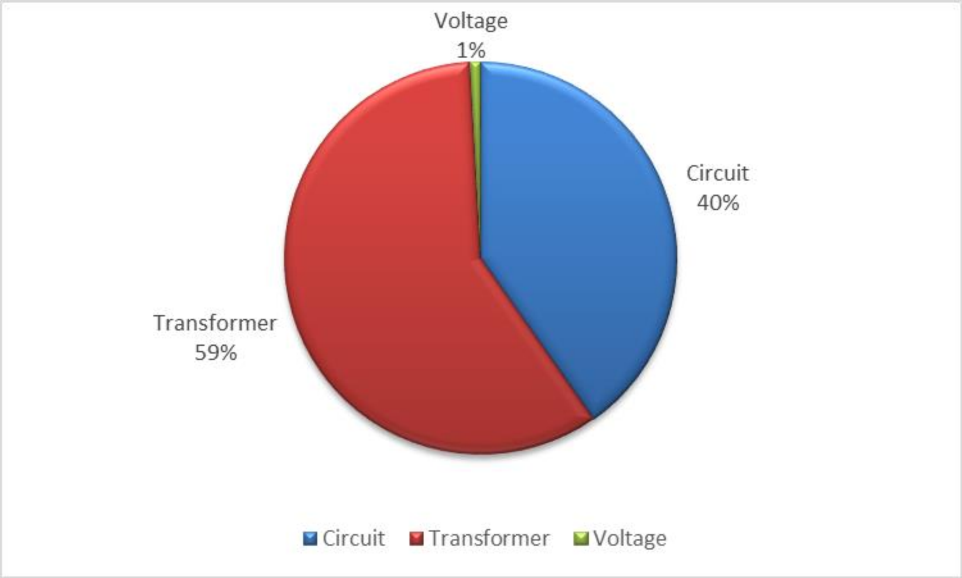

Figure 30 **Split of undiscounted investment by network constraint 2015 – 2050 (central scenario, smart incremental investment strategy)**

It can be seen that the majority of investment is caused by overloading of the transformer (at distribution and primary substation) level. As previously mentioned, transformer level spend occurs as a number of downstream feeders 'share' a transformer and hence the capacity of the transformer is apportioned equally across them. This accounts for approximately two thirds of the network investment.

The chart shows that there is minimal voltage related reinforcement, but this does not necessarily mean that there are very few voltage issues that are expected to occur. The Transform Model only reports on the 'primary' investment driver; i.e. if an asset is found to be exceeding both thermal and voltage limits in the same year, the model will only report on the greatest exceedance, which is highly likely to be thermal. As will be seen below in Figure 31, a number of the interventions that release thermal headroom also release voltage headroom (and legroom) meaning that a number of potential voltage-related issues are 'resolved' before they materialise as a second order effect of resolving the thermal issue.

Furthermore, it should also be recalled that the Transform Model operates on an 'averaged' basis, meaning that each feeder within a certain class shares many attributes. In reality, there will be minor differences between feeders, and there will always be some outliers. Such feeders will require investment slightly earlier than others and, as such, these feeders may well have an investment trigger that is different to the bulk of the feeders in the class. For example, if the bulk of the feeders experience a thermal overload slightly before they encounter voltage-related issues, there will be some feeders within the class that actually encounter voltage related issues first. The model does not capture this for all outliers and hence it is important to appreciate that there will still be a need in some cases to invest from a voltage, rather than thermal, perspective.

To further illustrate these points, a representative feeder from the Northern Ireland distribution network has been selected to demonstrate the drivers for distribution network investment. Figure 31 details the evolution of the different types of headroom for the "HV7 Rural Overhead Radial 11kV" feeder type in the "Central" scenario, smart incremental investment strategy for the period 2016 – 2050. This feeder serves as a good example of how the various headrooms described are eroded through the introduction of low carbon technologies, and then increased through the deployment of solutions.

It also serves as an example of the point made above that voltage issues do occur, but here it is found that voltage legroom is reduced to almost zero at the same time as a thermal threshold is breached and the expenditure has been logged as being triggered by the thermal issue rather than voltage, although the intervention deployed also resolves the voltage issue.

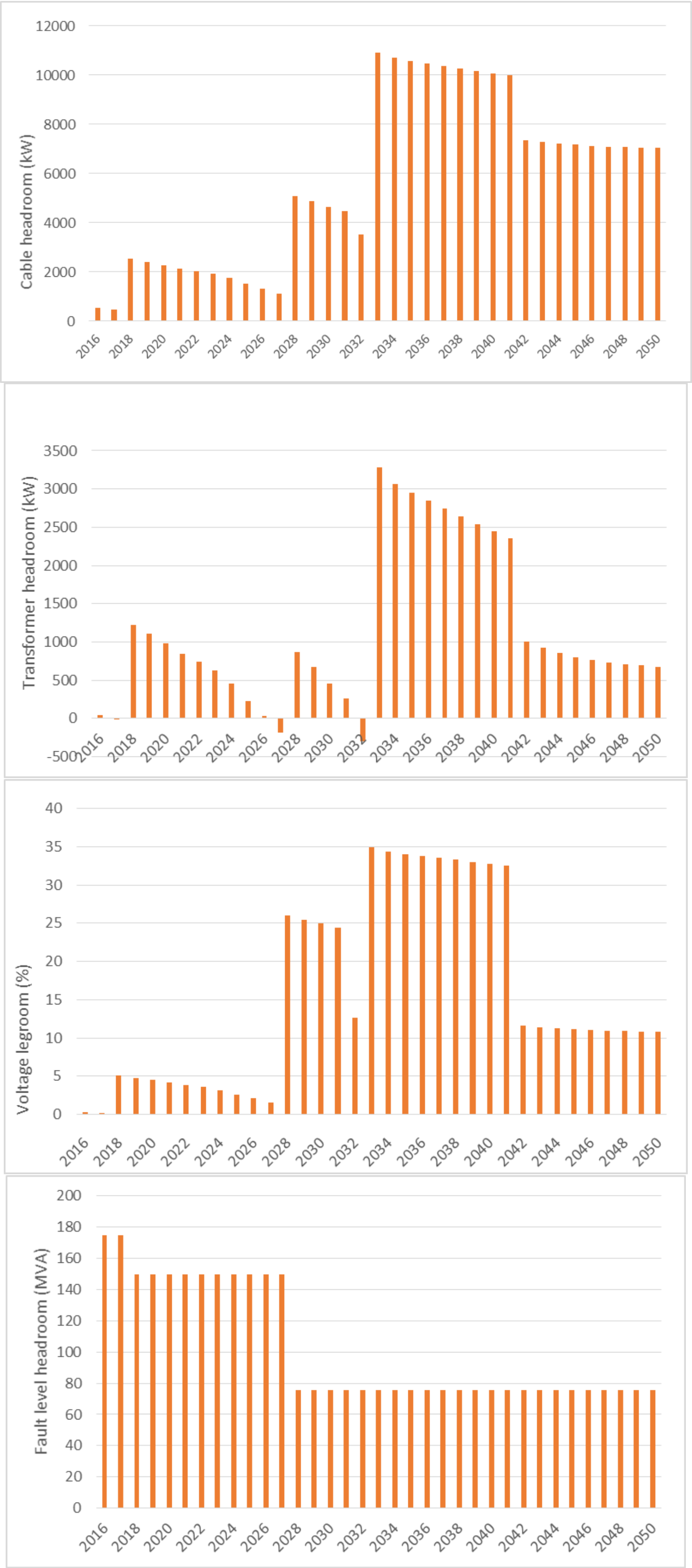

Figure 31 Distribution network investment drivers

In Figure 31, it can be seen that the first trigger for reinforcement occurs at the transformer (the second chart) as this becomes overloaded in 2017 (the headroom becomes negative). A solution is deployed to remedy this and restore a positive headroom, but it can also be seen that this solution has an effect on the other headroom classes. The voltage legroom in this year has also decreased to zero, but the solution to remedy the transformer headroom problem also remedies the voltage issue. On the other hand, the solution has a detrimental effect on fault level, causing this to rise and hence erode the fault level headroom slightly (bottom chart).

Two further headroom violations are found later in the modelled period in 2027 and 2032. In each case it is a breach of the headroom in the transformer and a similar behaviour to that described above can be observed. Solutions are deployed that also have a beneficial effect on the cable headroom and the voltage legroom, while in one case the fault level headroom is eroded and in the other case the deployed solution has no effect on headroom meaning it stays constant.

The precise nature of the solutions deployed on any feeder can be extracted from the model outputs.

6.4 Distribution network investment location

Future expenditure requirements for investment in distribution network assets are likely to be unevenly dispersed across different locations of the electricity distribution network in Northern Ireland. The extent to which the expenditure levels are distributed over the different representative feeders will depend on the number of customers connected (i.e. magnitude of base load), uptake levels of load and distributed generation related low carbon technologies and on the electrical characteristics of the substations and feeders under consideration.

In this sense, it is strategically important for NIE Networks to be able to identify and locate the areas within the distribution network that require relatively significant investment so that investment decisions can be prioritised and associated resources can be procured and deployed in a measurable and timely manner. Figure 32 presents the location of the distribution network investment driven by the uptake of low carbon technologies grouped by network voltage level at different time periods between 2016 and 2060. It should be noted that Figure 32 refers to the “Central” future energy outlook for the smart incremental investment strategy.

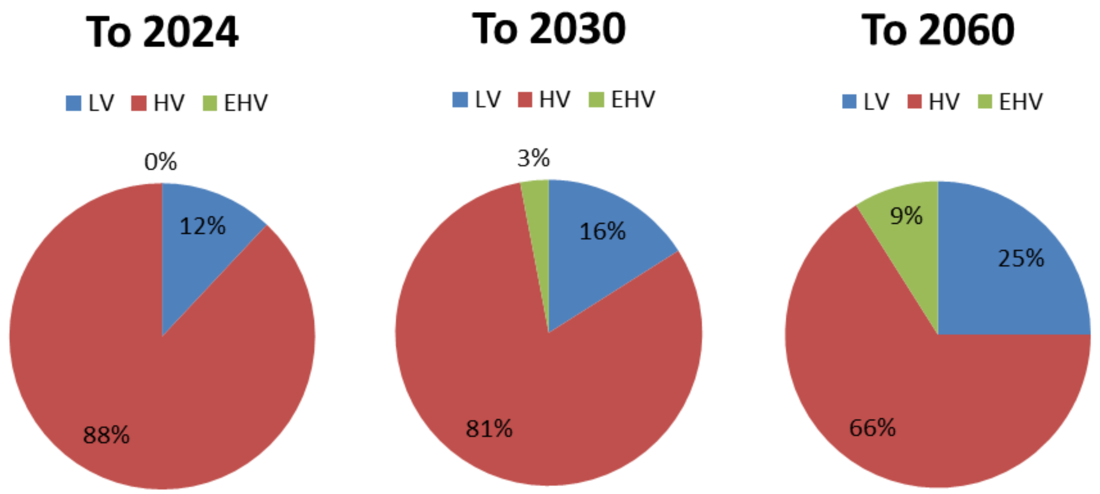

Figure 32 **Distribution network investment by voltage (gross totex costs)**

It can be seen from Figure 32 that during the period 2016 – 2024, the expenditure is focused mostly on HV. The reason for this is that the inherent LV headroom available in combination with the fact that the intervention threshold for LV assets is set at 100% means that the relatively low levels of LCTs connecting to the network can be accommodated at this voltage. However, the aggregate effect of numerous LCTs connecting in the same area means that the HV network experiences some overloading as a large number of LV feeders aggregate to a single HV feeder. Furthermore, at HV the threshold for intervention is somewhat lower than LV so as to account for being able to restore supply under outage conditions.

In the latter part of the modelled period EHV expenditure arises slightly more prominently. This occurs as a result of the growing load on numerous HV feeders supplied by the same EHV assets. However, as can be seen from the 2030 graph, this does not occur until the end of the modelled period, so should not be an area of key concern. In the period to 2030, 97% of the investment is at HV and LV and hence these areas should remain the focus of LCT related reinforcement.

Further to identifying the voltage levels at which the investment occurs, it is also possible to examine the specific networks responsible for instigating investment and their contribution to the overall network investment requirements can be quantified. Table 14 details network specific investment levels as a percentage of the future overall network expenditure for the ten distribution network types in Northern Ireland that are found to require the largest investment in the Transform Model. Table 14 was developed for the “Central” scenario, and the smart incremental investment strategy over the period 2016 – 2060.

Table 14 **Investment disaggregated by network type**

Feeder type	Network investment (% of overall expenditure)
HV7 Rural Overhead 11kV	31%
HV5 Mixed 11kV	12%
HV8 Single Transformer Primary 11kV	11%
LV5 Retail Park	10%
LV8 Terraced Street	6%
HV1 Town Centre 11kV	6%
EHV3 Rural Mixed Radial	4%
LV4 Industrial estate	4%
HV4 Suburban Underground 6.6kV	4%
EHV1 Urban Underground Radial	3%

As outlined above, the largest proportion of investment is found to be at HV as a result of the aggregation of a number of LV circuits (where low carbon technologies connect) onto one HV circuit. The intervention threshold at HV is also considerably lower than at LV meaning that the load is allowed to develop to the full asset rating at LV before triggering an investment whereas the intervention occurs earlier at HV so as to allow the re-supply of customers under n-1 conditions.

6.5 Distribution network investment solutions

Networks are made up of a range of technologies that are applied in different combinations and at different geographical scale to enable the transfer of energy from grid exit points to consumer load points. A range of smart solutions as well as conventional solutions for grid reinforcement are present in the Transform Model to deliver an economically efficient strategic plan for the long-term development of distribution networks in response to low carbon technologies on the customer-side. Table 15 displays the ten most deployed engineering solutions in the Northern Ireland distribution network over the period 2016 – 2050 when adopting the conventional investment strategy. By contrast, the top solutions selected when utilising the smart incremental investment strategy are given in Table 16. These sets of engineering solutions were found to be the least cost set to support the network integration of low carbon technologies within the “Central” scenario.

Table 15 **Solutions deployed under conventional investment strategy**

Rank	Conventional investment strategy
1	HV overhead network split feeder
2	EHV underground network split feeder
3	HV overhead minor works
4	Small 33/11 Tx
5	LV Underground network split feeder
6	Large 33/11 Tx
7	LV underground minor works
8	HV Underground network split feeder
9	LV Ground mounted 11kV/LV Tx
10	HV underground minor works

Table 16 **Solutions deployed under smart incremental investment strategy**

Rank	Smart incremental investment strategy
1	Small 33/11 Tx
2	Large 33/11 Tx
3	LV Ground mounted 11/LV Tx
4	Permanent Meshing of Networks - LV Urban
5	RTTR for HV Overhead Lines
6	Permanent Meshing of Networks - LV Suburban
7	Active Network Management - HV
8	Temporary Meshing (soft open point) - HV
9	LV underground minor works
10	Generator Providing Network Support e.g. Operating in PV Mode - HV

Table 15 and Table 16 show that the conventional and smart incremental strategies share in common four of the most deployed solutions. It is noticeable that while in the conventional strategy, HV overhead lines are often upgraded (solution 3) and LV networks are split (solution 5) to accommodate load growth and voltage drop issues, but instead in the smart incremental strategy the investment focuses on real time thermal ratings of such lines (solution 5), and the meshing of such LV circuits (solutions 4 and 6).

Detailed analysis of the volumes of different solutions deployed onto different network types is easily achieved by a user through interrogation of the model outputs for any particular scenario or study case.

6.6 Distribution network investment enablers

Enablers are component parts of a solution that are not able to provide headroom benefits when deployed on their own. Enablers are typically associated with monitoring, communications or control systems. Thus, enablers have the potential to be deployed separately from the solution itself, for example, a communications infrastructure could be laid down in advance and utilised for more than one solution application. Table 17 details the ten most deployed enablers in the Northern Ireland distribution network over the period 2016 – 2050 for the “Central” scenario.

Table 17 **Enablers deployed on the distribution network**

Rank	Smart incremental investment strategy
1	HV Circuit Monitoring (along feeder)
2	Dynamic Network Protection 11kV
3	EHV Circuit Monitoring
4	RMUs Fitted with Actuators
5	Advanced control systems – HV
6	Communications to and from devices - LAST MILE ONLY
7	Weather monitoring
8	Advanced control systems - EHV
9	Advanced control systems – LV
10	LV Circuit Monitoring (along feeder)

In the top down investment strategy, these three enablers are deployed as a strategic, up-front investment

It can be seen in Table 17 that the enablers associated with the most prevalent smart solutions are picked, such as circuit monitoring and weather monitoring for real time thermal rating of HV overhead lines.

Three enablers have also been highlighted as being included in the ‘smart top down’ investment strategy. These are the enablers that are deployed ahead of need to allow greater network visibility and facilitate the more cost-effective roll-out of certain smart solutions in the future.

In the default top-down approach, the three indicated enablers represent the only up-front investment. It is possible to further identify strategic investments that can be carried out if necessary. Examples of these might include updates to the control room functionality or investment in new network planning tools that allow for systems such as real time ratings to be more easily assessed by the network design and planning team. Numerous ‘back-office’ investments can be selected if desired, but owing to the relatively gradual initial uptake of low carbon technologies, it was not felt to be appropriate to include these. The reason for this is that the investment levels attributable to the top down strategy are significantly higher than those in the smart incremental strategy.

Overall, the split of investment between conventional solutions, smart solutions and enablers is shown in Figure 33 for a central uptake of low carbon technologies. It can be seen that investment in conventional approaches still accounts for the majority (57%) of the total investment, with the remaining 43% being split between the enabling technologies and smart solutions. This is because all of the investment in the early years (when discounting has very little impact) is in conventional solutions. Furthermore, the smart solutions deployed later have the effect of deferring investment in conventional solutions; although these conventional solutions are still needed towards the end of the modelled period, hence the significant amount spent on them overall. Finally, the conventional solutions tend to be higher cost, so even if they are deployed in lower numbers than otherwise might be the case, they will still make up a large proportion of this split by investment level.

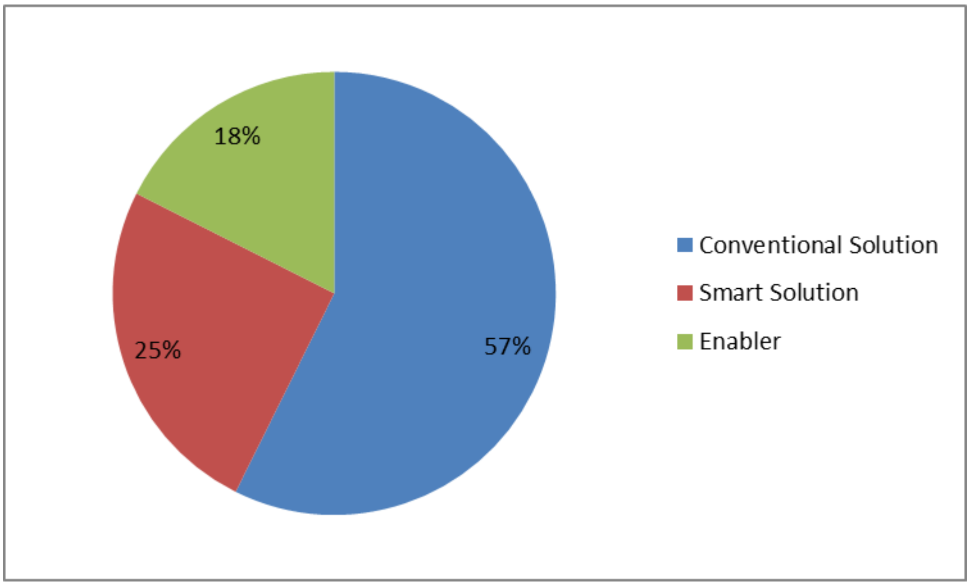

Figure 33 **Split of discounted investment by solutions and enabler categories 2016 – 2050 (central scenario, smart incremental investment strategy)**

6.7 Distribution network investment driven by LCTs

The results from the modelling indicate that the electrification of heat and transport leads to increased investment levels in the distribution network. Conversely, the additional penetration of distributed generation does not cause network expenditure, but rather can in some limited cases, assist in supporting the network by helping supply demand locally and increase voltages.

When considering the “Central” scenario for uptake and the smart incremental strategy, some £98m in discounted totex is forecast to be invested across the period to 2050. Of this figure, approximately £52m is entirely owing to heat pump connection, while approximately £40m is attributable to electric vehicles. The connection of further distributed generation actually reduces investment slightly (albeit the financial saving is measured in thousands rather than millions).

The remaining £6m is required in networks where it is a combination of heat pumps and electric vehicles together that trigger the reinforcement. This shows that while at first glance it may appear that electrification of heating poses the greatest challenge to the network, this composite effect of different demands growing simultaneously carries a significant impact.

It is important to note that this does not mean that accommodating distributed generation causes no challenges to the network. Rather, the results presented here are indicative of the fact that the uptake scenarios are ‘composite’, i.e. they are made up of the uptake of both demand and generation technologies. These two types of LCTs naturally complement one another to an extent and the investment tends then to be driven by those that increase demands and reduce voltage. If there were no demand technologies connecting (i.e. only generation was examined), then clearly this would cause voltage rise issues and would trigger investment.

7. Sensitivity Analyses

This section uses a sensitivity analysis approach to investigate the impact of key factors on distribution network investment. Each sensitivity assumes a change in one variable at a time, with all other assumptions being held constant in order to capture the impact of each variable in isolation. The analyses of sensitivity were divided into economic and engineering groups according to the nature of the variable to which the impact is to be measured.

Sensitivity analyses have been undertaken to explore the effect of:

- Economic parameters
    - Discount rate
    - Look-ahead period
    - Cost of conventional and smart solutions
    - Customer tariff driven charging of electric vehicles
    - Remove top three (smart) solutions
    - Clustering of low carbon technologies
- Engineering parameters
    - Thermal intervention threshold
    - Phase imbalance
    - Fast charging of electric vehicles
    - Solar photovoltaic and energy storage systems

The sensitivity analyses were performed for the “Central” scenario adopting both a conventional and smart incremental strategy to network investment over the period 2016 – 2050. Each sensitivity analysis is compared to a reference case (i.e. Central scenario for the respective investment strategy) presented in Section 6, allowing their impact on future distribution network investment to be quantified and assessed. This reference case is represented by the 0% line in Figure 34 and Figure 35.

The impact of each sensitivity on load-related expenditure associated with the uptake of low carbon technologies is expressed in percentage change of the NPV of grid expenditure with respect to the reference case. Negative change represents a percentage decrease whilst a positive change represents a percentage increase both from the reference case. The blue bars show the difference under the conventional investment strategy, while the orange bars represent the changes in a smart incremental investment strategy.

For example, the change in investment required if a higher intervention threshold is used (5% higher than the default), then investment expressed in NPV terms is expected to be 25% lower than the base case investment for a conventional investment strategy, and 27% lower than the base case under the smart incremental investment strategy as greater levels of LCTs can be accommodated before reinforcement is required, meaning investments are triggered later, and hence become ‘cheaper’.

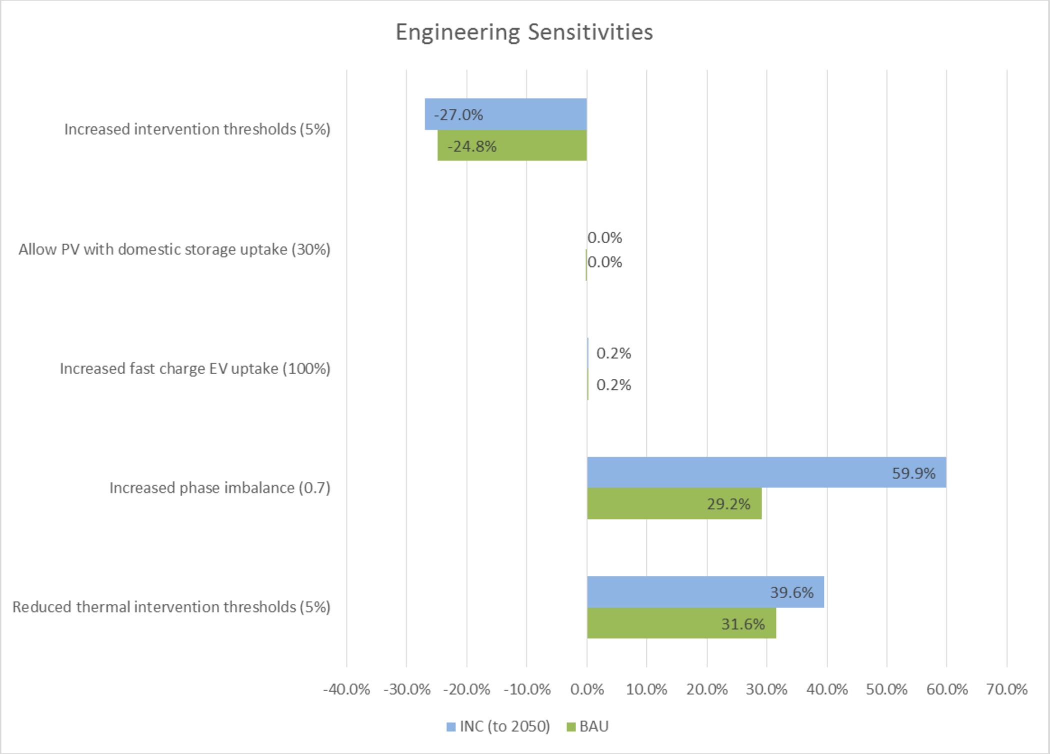

Figure 34 **Sensitivity analysis to engineering parameters (Central scenario)**

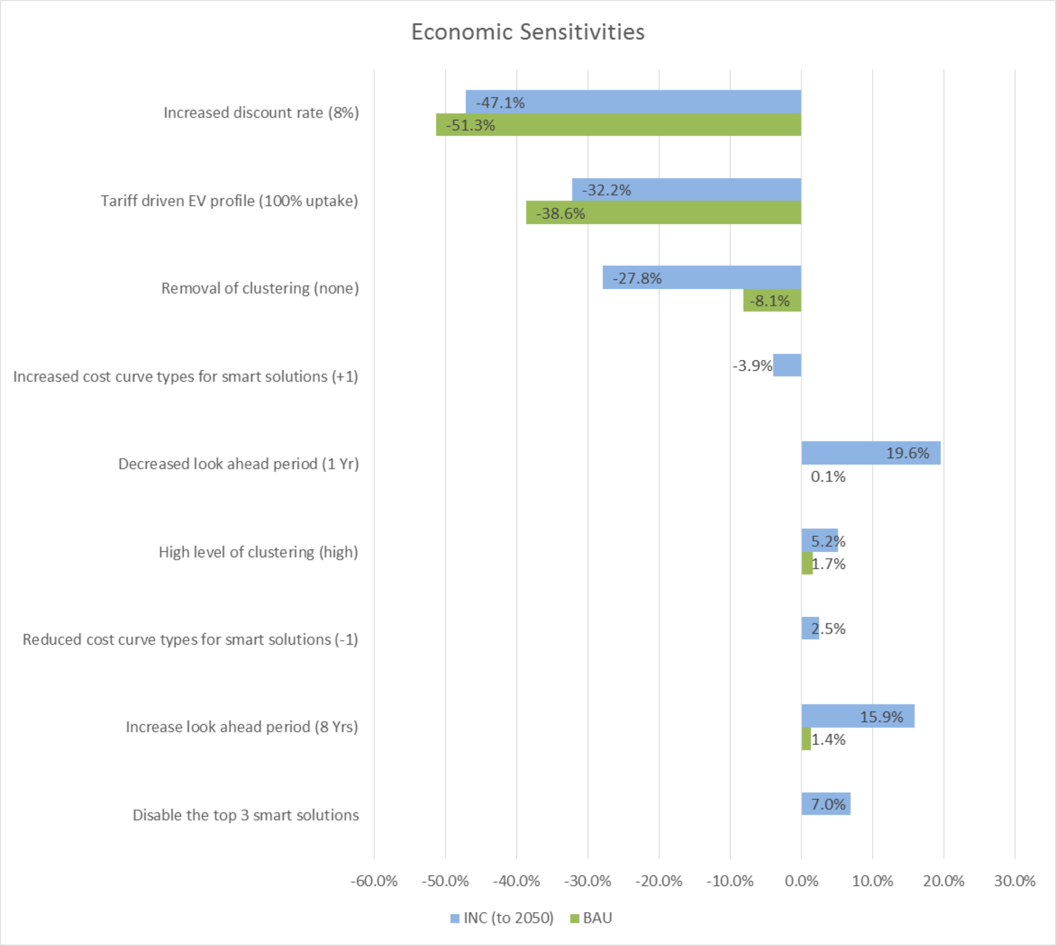

Figure 35 **Sensitivity analysis to economic parameters (Central scenario)**

7.1 Discount rate

The Transform Model uses a discounting procedure to compare costs and benefits that occur in different time periods. The concept of discounting is based on the ‘time preference’ principle where people, generally, prefer to receive goods and services now rather than later. The discount rate considered in the NPV calculation of future network expenditure streams is the social time preference rate, which is commonly used by UK Government. This is equal to 3.5% over the period to 2045 and 3% beyond 2045.

This sensitivity analysis explores the impact of employing a different discount rate in the calculation of the NPV of future network expenditure. The sensitivity considers a higher discount rate than the reference case and it is equal to 8%. Figure 35 shows that a higher discount rate results in a lower NPV of grid expenditure for both conventional and smart investment strategies by 51% and 47% respectively. Distribution network investments made later in the period of analysis cost proportionally less than those of reduced discount rate.

It should be noted that the discount rate does not affect the distribution network investment profile based on gross expenditure as this is undiscounted.

7.2 Network planning horizon or ‘look-ahead’ period

The Transform Model employs a perfect foresight approach to network investment. Thus, distribution network investment decisions are made with a perfect view of network loads in the forward years. Solutions are therefore selected on the basis of them being able to cater for the network demand over the coming years, and this number of years, which can be thought of as a network planning horizon or a look-ahead period, is set as a default to five. This sensitivity analysis studies the impact of selecting different look-ahead periods on expenditure requirements for the development of the distribution network. The sensitivity assumes look-ahead periods of 1 and 8 years.

Opting for a look-ahead period of one year and a smart incremental strategy, network investment decisions to accommodate short term growth of low carbon technologies are based on the deployment of low cost solutions that release low levels of headroom. This is likely to become cost inefficient in the long term as these solutions will need to be replaced by those that have significant ability of releasing larger volumes of headroom. Hence the model shows an overall increase in investment of almost 20% through having to repeatedly invest in the same portions of network. Furthermore, this approach to network investment suggests that a large number of solutions are required to be replaced before reaching the end of their asset life, which is unlikely to be desirable. The limited portfolio of solutions available in the conventional strategy, and the fact that they tend to deliver significant headroom gains, generally means that the same solution is selected for a one year look-ahead period as for a five year period given that the volume of headroom release is significant and the life of the solution is usually of the order of decades.

For a look-ahead period of eight years, engineering solutions that can provide sufficient headroom for a longer period are broadly favoured. Conventional solutions are fit for this purpose as they provide step change increase in headroom and have long asset lives. Therefore, Figure 35 displays no discernible impact in the conventional investment strategy. Under the smart incremental investment strategy, Figure 35 indicates an increase in expenditure of 16% as some of the preferred solutions can only deliver the headroom required for a shorter period. This means that more expensive solutions, or combinations of solutions, are being selected to ensure that the network can accommodate the three years’ additional load growth before further reinforcement is necessary.

7.3 Cost of smart solutions

The Transform Model applies a cost curve approach to project future costs of conventional and smart solutions. Figure 36 displays the five generic cost curves present in the Transform Model rebased for the economic reference year zero. The cost curves were developed from a selection of real-world technologies combining an extensive range of different factors such as volume, material cost price changes and learning curves, from both within and out of the energy sector. A cost curve is associated with each conventional and smart solution to allow the future costs of engineering solutions to be approximated based on similar technologies.

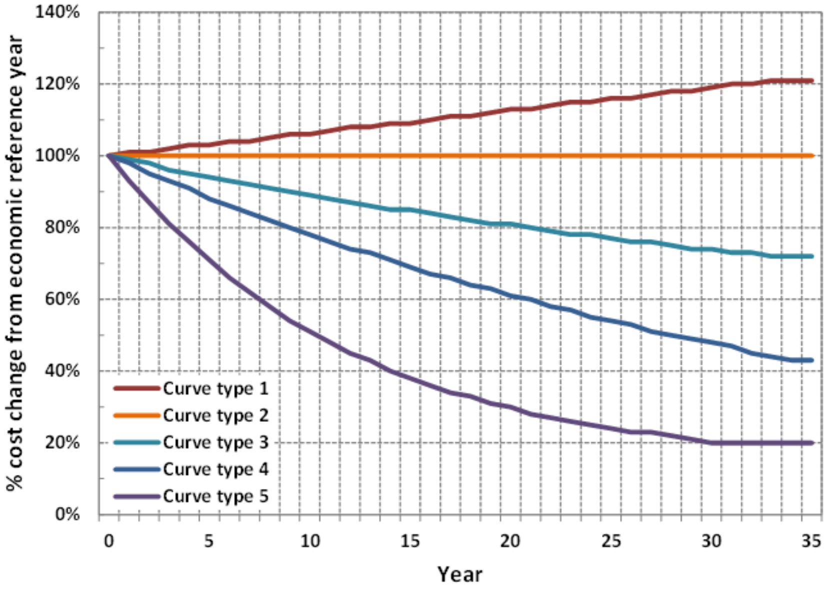

Figure 36 **Cost curves for conventional and smart solutions**

In Figure 36 the curve type 1 represents future rising costs of technologies that are inferred from average cost curves of steel and aluminium. This rising curve is generally associated with conventional solutions for traditional grid reinforcement. Curve type 2 is a flat curve reflecting no future change in the cost of technologies. Curve type 3 denotes a low reduction in future cost of technologies and was derived from the average cost curves of some renewable generators and some flat line relationships. Curve type 4 characterises a medium reduction in future cost of technologies based on average cost curves of offshore wind farms. Curve type 5 reflects a high reduction in the future cost of technologies driven by the average cost curves of information technology equipment.

This sensitivity analysis changes the cost curve associated with each conventional and smart solution and quantifies its effect on distribution network investment. The analysis firstly explores the impact of achieving lower costs and a faster roll out of smart solutions by producing a step change increment in the original cost curve of each smart solution. Secondly, it explores the impact of attaining higher costs and a slower roll out of smart solutions by creating a step change decrement in the original cost curve of each conventional and smart solution.

It can be seen in Figure 35 that changing the cost curves up to represent a lower cost of smart solutions produces a saving in investment of 4% when adopting the incremental strategy, while lowering the cost curves and thereby increasing the costs of smart solutions, results in a 2.5% increase in total expenditure. This shows that the model is broadly insensitive to these variations in costs associated with smart solutions. This demonstrates that even if smart solutions are slightly more expensive or slower to materialise than first thought, the impact on overall investment is likely to be low, thereby providing some reassurance that any potential cost savings are not entirely contingent upon the exact costs of a small number of solutions.

7.4 Customer tariff driven charging of electric vehicles

Smart charging strategies for electric vehicles are part of the range of smart grid solutions present in the Transform Model to mitigate limited network headroom as a result of the load growth imposed by the connection of low carbon technologies. This smart charging strategy is considered to be DNO-led (e.g. direct EV charging control strategy) and therefore competes against other smart and conventional grid solutions and is selected based on technical and cost-efficient grounds.

Customer-led charging of electric vehicles, incentivised by time of use tariffs, has the potential to lower the requirements for network investment compared to non-incentivised charging. Allocating the charging of electric vehicles to times of day characterised by lower electricity demand and consequently prices is likely to reduce the peaks of load in the distribution networks.

This sensitivity analysis studies the effect of time of use incentives for charging of electric vehicles by shifting the charging profile in line with an off-peak charging regime. Figure 35 suggests that the potential impact of customer tariff-led charging of electric vehicles can be significant. Future grid expenditure related to low carbon technologies is quantified to decrease by 32% in the smart incremental strategy and 39% in the conventional investment strategy. It should be stressed that these outcomes assume that all electric vehicles are charged in accordance with this off-peak regime. In reality, a proportion of electric vehicles will still be charged at peak time. Nonetheless, this sensitivity analysis indicates that should electric vehicle uptake become significant, there is distinct merit in exploring the feasibility of utilising incentives for off-peak charging to reduce the impact on network investment.

7.5 Clustering of low carbon technologies

The growth rate of connection of low carbon technologies in different types of LV network is generally driven by a set of rational factors regarding regional differences, investment behaviour of consumers and suitability of technologies to the different building types present on different types of LV network. Similarly, it is likely that low carbon technologies will cluster in certain areas due to less rational factors (e.g. several homeowners along a street decide to invest in solar photovoltaic to resemble the neighbours), leading to significant load increase in these network areas and hence significant distribution network investment. In order to account for this, the Transform Model considers various ‘cluster groups’, ranging from highly clustered to weakly clustered. The uptake rate of different low carbon technologies is then apportioned within these groups according to customisable levels of clustering.

This sensitivity analysis investigates the effect of the use of different clustering levels of low carbon technologies in distribution network investment. Figure 37 details the different clustering levels of low carbon technologies considered in the analysis. The standard clustering level is taken from the extensive GB experience of wide-scale uptake of domestic level solar PV generation.

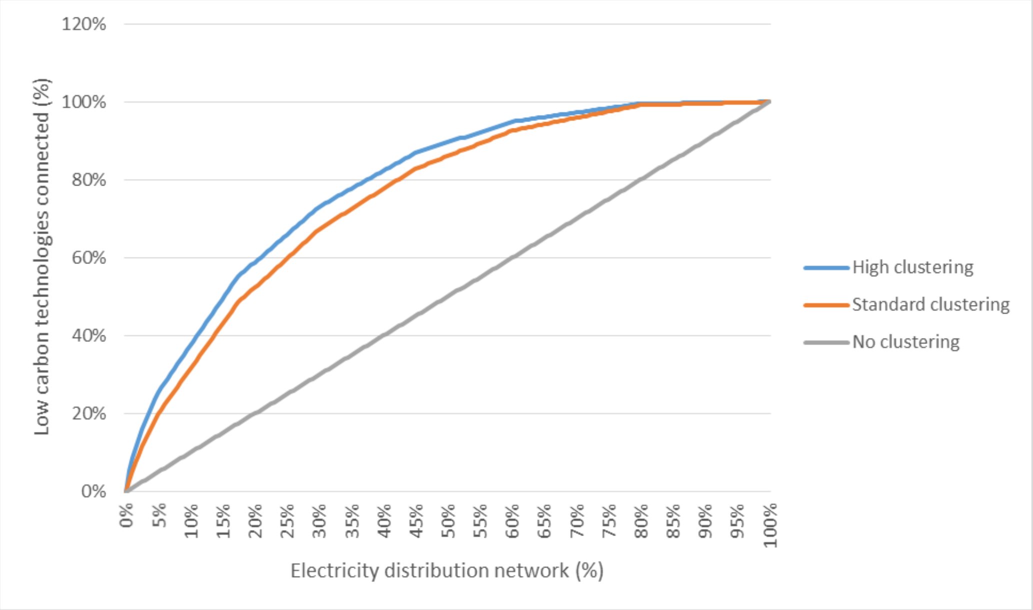

Figure 37 **Clustering of low carbon technology installations in distribution networks**

It is seen in Figure 37 that for the case of no clustering, there is a linearly increasing trend in the distribution of low carbon technologies across the network. For instance, there is a 25% uptake of low carbon technologies over 25% of network. As the clustering effects become more dominant, low carbon technologies are connected in closer geographic proximity contributing to a decrease in circuit headroom. Higher levels of clustering tend to produce higher levels of distribution network investment (especially earlier in the period of analysis).

It can be seen in Figure 35 that without clustering there would be an 8% reduction under conventional investment and a 28% saving under smart incremental investment in the necessary expenditure. This is because the uptake levels are spread, not impacting on the thresholds of any particular networks. The effect of the higher level of clustering is seen to be less pronounced, only registering less than a 2% increase under the conventional investment strategy, and a 5% increase in the smart incremental approach. The reason for this is that this greater level of clustering does not particularly stress the network more than the 'standard' level of clustering used as a default because the differential between the standard and high levels is fairly small. On the other hand, the difference between the standard level of clustering being present and there being no clustering is sizeable and has significant impact.

It is highlighted that the rate of uptake of low carbon technologies remains unchanged while the way in which they cluster is the only changing variable in this analysis. Particularly in the early part of the modelled period, it is the amount of clustering that drives the necessary expenditure and hence this is a fairly important parameter.

7.6 Remove top three smart solutions

It is possible that some smart solutions may not be suitable for mass roll-out or may be inapplicable to NIE Networks longer term strategy. To assess the sensitivity of the model to the availability of specific smart solutions, the three smart solutions that are selected most often have been disabled. The model is therefore required to select the next best solution to resolve the headroom constraint.

By doing this, it can be seen that overall expenditure increases in the smart incremental strategy by 7%, showing that the model is broadly insensitive to the availability of specific solutions and should NIE Networks pursue alternative solutions, it is likely that the LCT uptake can be satisfied through deployment of these alternative solutions without unduly increasing network investment.

7.7 Thermal intervention threshold

The Transform Model looks to reinforce networks through the deployment of engineering solutions when the levels of headroom of circuits or substations reach a pre-specified threshold termed as the intervention threshold. These thresholds relate to the load expressed as a percentage of the rating of an asset that can be tolerated before reinforcement is required. For instance, for a HV cable the intervention threshold may be set to 60% of the rating of the cable to allow for the interconnection that exists transferring load in the event of circuit outages. For LV cables this parameter may be set at 100%. The intervention thresholds were provided by NIE Networks at a workshop with EA Technology for the different network voltage levels and feeder types.

This sensitivity analysis examines the impact of setting different circuit and substation intervention thresholds on distribution network investment. The sensitivity assumes intervention thresholds varying from 5% below to 5% above those of Table 8, i.e. if the intervention threshold was originally set to 60%, it will now be considered at 55% and 65%.

It can be observed in Figure 34 that under a smart incremental approach to network investment, a 5% reduction of the substation intervention threshold leads to 40% rise of grid expenditure whilst a 5% rise in substation intervention threshold results in 27% lower expenditure requirements. For example, if a circuit was thought to be permitted to be loaded to 60% of its rating under standard practice, but this was then changed to 55% of rating, the resulting increased level of investment would be significant. Under a conventional investment strategy there is a 25% lower cost associated with a reduced intervention threshold and 32% higher costs associated with an increase in the intervention threshold compared with the default results under the conventional strategy.

These results indicate that the intervention thresholds are extremely important parameters as they effectively describe the level of risk that can be taken by the network in operating so as to permit the restoration of supplies under outage conditions.

7.8 Phase imbalance

Electricity customer connections have not always been evenly spread between the three phases as the LV networks continue to evolve. Furthermore, different electrical energy demand from different customers is generally not considered when making new LV connections. As a result, it is likely that the three phases will be unbalanced. The magnitude of phase imbalance will have an impact on the thermal rating of network assets such as feeders and transformers.

This sensitivity analysis investigates the impact of the magnitude of phase imbalance on network investment requirements. In the Transform Model, the magnitude of the phase imbalance is represented by the effect that it causes on the thermal rating of network assets. The assumed level of phase imbalance is described in Appendix V. This sensitivity considers that the phase imbalance is more severe than that initially assumed. For example, for an initially assumed phase imbalance of 0.9, this sensitivity considers a value of 0.7 for phase imbalance. As a result, the Transform Model de-rates the nominal rating of the assets to 70%.

Figure 34 demonstrates that the effect of increasing the phase imbalance is very significant as the network expenditure linked to low carbon technologies increases by around 29% for the conventional strategy and by 60% for the smart incremental strategy. This observation is important as phase imbalance has in practice been difficult to quantify. Once electricity distribution customers add significant loads, such as electric vehicle charging, onto single phase connections, the results of phase imbalance can be exacerbated. It may therefore be prudent to consider the ‘default’ phase imbalance ratings of 0.9 as offering something of a ‘best-case’ in reality and investigations into the observed level of phase imbalance on the network could inform the future refinement of this parameter.

7.9 Solar photovoltaic and energy storage systems

Technological advances due to increased global research and development may lead to a relatively early breakthrough in battery technology. As a result, battery costs may fall considerably allowing distributed solar photovoltaic generation systems to be coupled with energy storage systems (e.g. home battery) and become a cost competitive technology to the mass market following its wide spread adoption. To this end, the solar photovoltaic uptake trajectories consider the customer adoption of this technology across the three scenarios.

The energy storage charges using electricity generated from solar panels (although it could also be charged when electricity prices are low under variable tariff schemes) and powers the home in the evening, when electricity load (and potentially prices) are high. The operating regime of the solar photovoltaic and energy storage system used for the purpose of this work is depicted in Figure 38 for an average summer weekday.

In the Transform Model the only domestic storage that is connected is partnered with a solar PV generation and it is only charged directly from the local generation. It is assumed that there is no variable pricing present to influence customer behaviour towards charging at times of low load and discharging at times of high load.

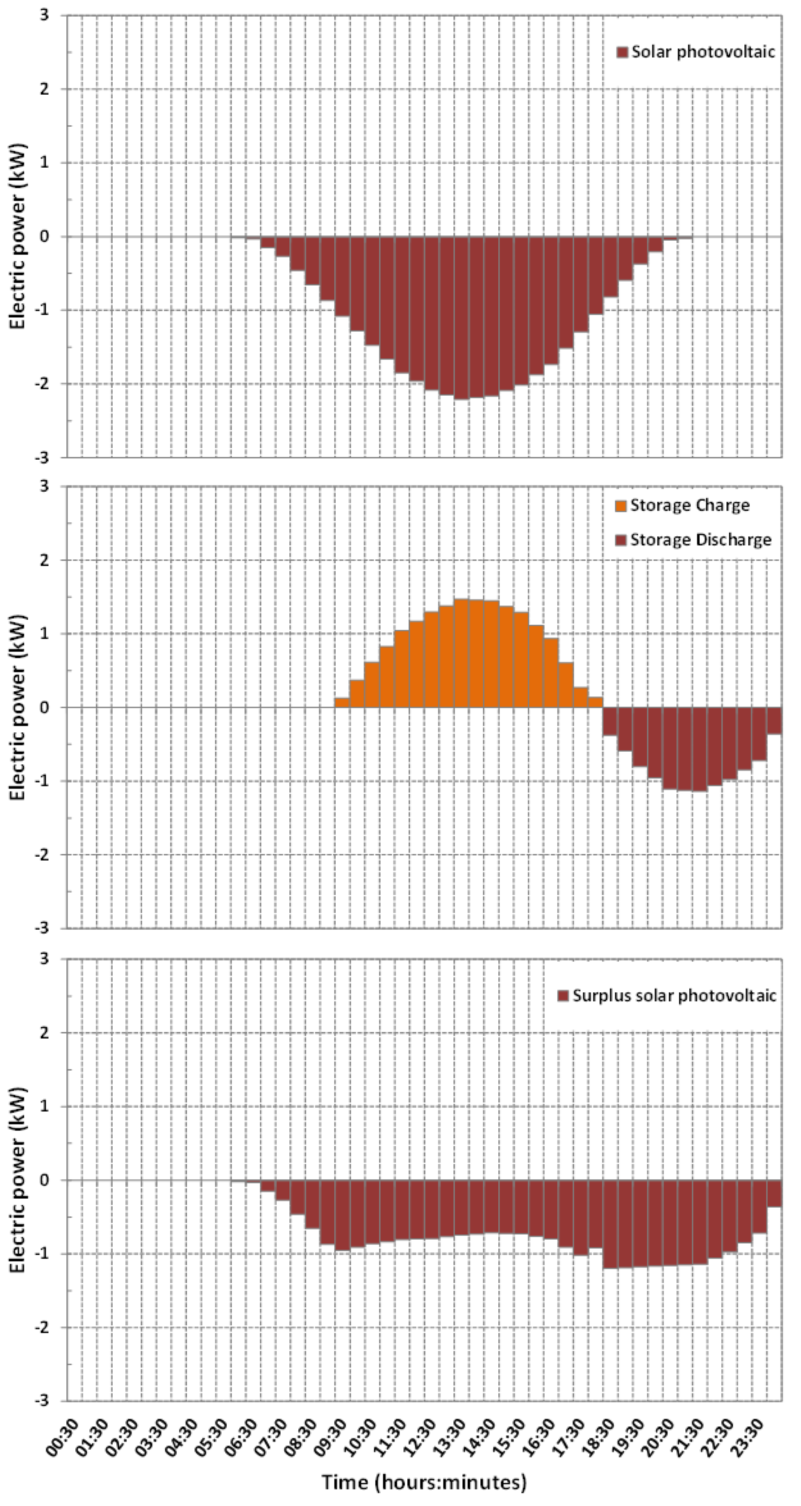

Figure 38 Operating regime of solar photovoltaic and energy storage system

Figure 38 considers 3kW installed capacity of a solar photovoltaic installation and 3kW power capacity of the energy storage with an energy capacity of 11kWh. It can be seen in Figure 38 that the energy storage charges during periods of coincidence of high solar power output and low load (i.e. during the day) and discharges during periods of coincidence of low solar power output and high load (i.e. evenings). The impact of this mode of operation results in reduction of the home peak and energy load which in turn lead to a decrease of the load seen by distribution networks.

This sensitivity analysis explores the impact on network investment of customers adopting home storage in concert with solar photovoltaic. The sensitivity assumes that 30% of all solar PV installations over the modelled period have associated domestic energy storage.

It can be observed in Figure 34 that the addition of domestic energy storage has negligible effect on the required levels of investment (at a 30% penetration rate). This suggests that customers adopting this behaviour does not materially benefit NIE Networks in terms of deferring network investment.

A potential reason for this is that during the winter season, when the network experiences the greatest constraint issues, the magnitude of the power output from the solar photovoltaic generation is significantly reduced compared to the summer season. Consequently, the amount of energy that can be stored is similarly reduced, and hence the change to demand experienced by the distribution network is less than that observed during the summer season.

7.10 Fast charging of electric vehicles

Technological advances in battery technology may contribute to a technological shift in the charging regime of electric vehicles from slow to fast charging. The Transform Model uses a technology neutral approach to electric vehicle batteries assuming a 3kW power capacity for slow charge batteries and 7kW power capacity for fast charge batteries both with a 22kWh energy capacity. The wide spread adoption of fast charging technology for electric vehicles may cause an impact in future expenditure requirements for the development of electricity distribution networks. This sensitivity analysis studies the impact of a technological shift in the charging regime of electric vehicles by substituting all the domestic slow charging batteries to fast charging.

The use of fast charging technology shortens the time over which the charging process of electric vehicles occurs at the expense of increasing the amount of power drawn from the distribution network for this shorter period. (Electric vehicle charging profiles are given in Appendix III.) Nonetheless, Figure 34 indicates that the impact on overall distribution network expenditure is negligible. This is perhaps a consequence of the fairly low uptake rates of EVs meaning that a significant number are required to trigger an intervention, irrespective of whether they are charging at 3 or 7kW.

8. Strategic Business Implications

This section briefly explore some of the wider implications of the results from the Transform Model, looking at how these can inform strategic business decisions rather than focusing on the results from an investment perspective.

8.1 Scenario modelling addresses uncertainty

There is considerable uncertainty regarding uptake levels of new low carbon technologies, both in terms of how many there will be, and where they will connect. This leads to consequential uncertainty in the level of investment that accommodating them will require.

It is therefore important to understand the likely bounds of this investment so as to be able to manage the uncertainty between the upper and lower bound. This can help inform business strategic positioning, such as decisions taken in the shorter term, which can have implications for the longer term. For example, investing a little more in the network today may allow for far greater opportunity to flex the network in the future to meet the demands imposed by a sudden upsurge in electric vehicle uptake, whereas an equally valid technical solution to meet today's requirements, may not allow such flexibility and lead to a far greater 'whole life' cost.

These aspects may raise important considerations for regulatory frameworks, and are likely to have consequences for consumer service quality and bills. A well-founded and consistent approach to scenarios, data and modelling can be expected to form a helpful basis for dialogue with regulators, customers and wider stakeholders.

8.2 Use of smart solutions to help mitigate risk

There are different ways in which network operators can invest in their networks to meet the challenges created by the uptake of low carbon technologies. The conventional approach is to install new assets (such as transformers, overhead lines, and underground cables) as and when the network requires reinforcement. In this way additional capacity is created in the network to cater for the increased demand. Such investments tend to produce significant step-increases in capacity, but sometimes with significant costs and installation times.

It has been observed that adopting a conventional approach results in a much greater level of uncertainty between the three scenarios as we progress through the timescale (i.e. the three lines diverge much more). This means that even by 2030, there is a 'spread' between the three scenarios for conventional reinforcement of £37m (i.e. the difference between expenditure for the low and high scenarios when investing 'conventionally' is £70m in 2030), as shown in Figure 28. By contrast it may be possible to adopt a 'smart' approach of combining new traditional assets with a mix of innovative smart solutions or processes (such as dynamic rating, active network management, demand side response etc.). By taking this approach the divergence between the scenarios is far less (approximately £27m at 2030 – see Figure 29), meaning it is easier to flex to cater for step changes in uptake of new technologies.

However, in order to realise this potential benefit, one must have the capability to deploy all of the solutions that the model recommends. If this is not possible, then other, more expensive or less efficient solutions will be utilised.

In reality, before any of these approaches can be deployed, they will have had to have been subject to a full process of trialling, testing, policy development and subsequent integration to business as usual. Such a process typically takes a minimum of 3 – 5 years to be fully integrated within network operators businesses. If such a process can be commenced as soon as possible, this means that a number of the smart solutions can then be available and ready to be deployed when the uptake scenarios start to significantly increase and the associated investment levels begin to diverge more in the early 2020s. However, if the research, development and demonstration of such approaches is not carried out ahead of this increase in uptake, then the potential benefits of adopting these approaches will be deferred significantly, leading to higher investment requirements.

8.3 Resourcing and skills requirements

The trialling and deployment of innovative smart solutions on networks requires a different skillset to the deployment of conventional assets. The Transform Model quantifies the level of each of these solutions to be deployed as a consequence of low carbon technologies connecting to the network, which in turn informs future skills requirements and the potential need for partnerships and service provision.

Furthermore, the Transform Model can help target future innovation requirements as the model indicates the likely smart solutions that will deliver best value within Northern Ireland in responding to the increased level of customer technologies. Those smart solutions that are deployed most often, or that are relevant to the network areas indicated as being most prone to overloading, can then be prioritised for further investigation and development. This ensures that any innovation projects that are initiated can have the best chance of delivering a quantifiable return on investment by assisting NIE Networks in investing in efficient networks going forward.

As the low carbon technologies tend to connect at low voltage, it might be expected that the majority of investment requirements occur at this voltage level. Indeed, initially a reasonable amount of the investment is seen to be at LV.

However, looking upstream, it can be seen that at the HV level, a reasonably large number of LV assets aggregate onto one HV circuit (or substation). As such, many small incremental changes in demand at LV aggregate to a more significant increase at HV, driving a large amount of the investment. This explains why the Transform Model predicts that the majority of investment over the longer term will occur at the HV level.

The model apportions transformer capacity across the number of circuits that the transformer supplies. In many cases, a large number of circuits are dependent on a single transformer, which means the model indicates that it is at this transformer (or substation) level that the majority of the investment is required, rather than at a feeder level. Therefore trialling and investment in novel solutions is likely to deliver the greatest return if these solutions focus on the areas which will see the greatest challenge (i.e. substations at the HV level).

9. Conclusions

The key findings of the analyses can be summarised as follows:

C1. This work has produced a fully populated, complex model representing the Northern Ireland electricity distribution network

(1) The model has a significant number of configurable parameters

(2) The model is dependent on a number of key inputs, particularly the scenarios for uptake of low carbon technologies

(3) It has been constructed using best available data from public sources and NIE Networks

(4) It is not intended to provide a single definitive answer, but rather to assist in informed dialogue and strategic decision making in this complex and evolving area

C2. The model is only concerned with the effects of, and investment attributable to, low carbon technologies

(1) The model should not be seen as a replacement for existing processes to calculate investment requirements

(2) It does not attempt to quantify the costs associated with other DNO activities such as asset renewal or managing new connections; rather the figures it provides are solely related to low carbon technologies

C3. Some headline outcomes from the model

(1) The level of investment driven by low carbon technologies is heavily dependent on the rate of uptake of such technologies (anticipated to be £78m - £370m on a discounted present value basis over the period to 2060)

(2) The initial investment requirements (over the first seven years) are relatively low (approximately £3m per annum on average) while the network has sufficient capacity to meet the needs of the new demands, but are likely to increase from the early 2020s (to approximately £7m per annum) unless smart solutions can be readily adopted at this time

(3) Certain network types are likely to experience greater changes than others, but there will be localised ‘hot-spots’ from clustering meaning that no individual network is necessarily immune to the challenges

C4. Some more specific points

(1) Energy efficiency gains over the coming years mean that underlying demand may not rise significantly; but certain new low carbon technologies (such as

electric vehicles) are unlikely to experience efficiencies in the same way, meaning that these loads have a more dominant effect

(2) The main investment driver is found to be due to thermal overload appearing at a substation level rather than a feeder level at the HV (and to a lesser extent LV) voltages

(3) The parametric model indicates that managing voltage drop as well as load will pose a challenge to NIE Networks going forward and while generation is unlikely to drive investment, it can have a minor beneficial effect in helping managing these voltage issues

C5. The model suggests that benefits can be derived from adopting a blend of smart and conventional solutions on the distribution network

(1) It is important to note that the costs associated with smart investment here represent a near best case whereby NIE Networks has access to the full inventory of solutions when required (in the early 2020s)

(2) In reality, it will be necessary to thoroughly research, trial, and implement into business as usual policies and practices concerning a number of the solutions to realise this benefit

(3) The model can assist in indicating which solutions are likely to provide the best value in this respect and hence can inform targeted research, development and demonstration projects

(4) Adopting this blend of solutions allows for a smoother investment profile and makes it easier to manage risk and respond to changes in uptake of low carbon technologies

C6. The model can be sensitive to certain parameters, such as the level of clustering of low carbon technologies and the charging behaviour of customers with electric vehicles

(1) The model demonstrates the savings that can be made through appropriate incentivisation of EV charging as network impacts can be significantly reduced if charging takes place at times when there is greater headroom (i.e. times other than the evening peak)

C7. Other wider points

(1) The use of some of these smart solutions to manage networks going forward will add complexity and will require different skills to those that may be currently prevalent within NIE Networks

(2) The model does not currently take account of any regulatory treatments which may bias the selection of certain solutions

(3) The model does not consider in its default case the use of incentivised tariffs for customers to move their demand to off-peak times (although this is explored within sensitivities)

C8. Some potential next steps

(1) The model is not intended to provide a single definitive answer; rather it provides a useful framework for discussion and can be updated as more up to date, or detailed information becomes available (regarding, for example, clustering levels, uptake rates of low carbon technologies, costs and benefits of smart solutions)

(2) The possibility of continually refreshing the model with such information from sources such as the learning currently emerging from a large amount of smart grid projects in Great Britain should be considered

Appendix I Quality Assurance

Quality assurance (QA) in the context of modelling platforms refers to processes that ensure the model's inputs, processes and outputs meet its quality requirements, manage risk of errors and ensure the model is fit-for-purpose. It is a key mean of ensuring models are robust and reliable meeting EA Technology's internal standards and most importantly client's expectations.

The development of the Northern Ireland version of the Transform Model followed a detailed QA process throughout the four key stages of the model development lifecycle (i.e. (i) scope, specify and design; (ii) build and populate; (iii) test; and (iv) deliver and use). EA Technology selected the appropriate QA process based on the various engagements with NIE Networks ensuring a shared understanding about the purpose and limitations of the model. The QA process was proportionate and tailored to the level of risk inherent to the Transform Model and its use.

EA Technology followed internal guidelines for quality assurance of models[17] that are in line with its British Standard BS EN ISO 9001:2008 certification under EA Technology's project management procedures.

The following table illustrates the checks that have been made and the various data sources used for the creation of the Transform Model for Northern Ireland.

Table 18 **Derivation and validation of parameters in Transform Model for Northern Ireland**

	Parameter	Data Source	Checking process
1	Ratings of circuits	○ Taken info from NIE Networks ○ At higher voltages, averaged from population and at LV averaged from samples	All values presented to NIE Networks for approval and validation
2	Number of circuits	○ Based on data obtained from NIE Networks	All values presented to NIE Networks for approval and validation
3	Apportionment of circuits between type	○ Probable combinations agreed with NIE Networks ○ Numbers reconciled against bottom-up data to ensure total numbers of circuits align with reality	All values presented to NIE Networks for approval and validation
4	Starting load and fault level on circuits	○ At higher voltages, loads and fault levels based on real data from NIE Networks ○ At LV, based on engineering judgement of NIE Networks staff in conjunction with EA Technology regarding the likely loads experienced on different feeder types	All values presented to NIE Networks for approval and validation
5	Assumption around the 'average' commercial load	○ Assessment of a number of specific feeders within Northern Ireland that are known to have commercial load to derive an appropriate profile for commercial demand ○ This was then reconciled with total demand	Checked by EA Technology and compared with GB figures to ensure validity

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[17] EA Technology, 2014. "Modelling Quality Assurance Guidelines", Chester, United Kingdom, March 2014.

	Parameter	Data Source	Checking process
6	LV connected wind generation	○ NIE Networks provided information regarding the number of LV networks that have been installed solely to support wind generation ○ Profile for wind generation taken from average size of generator multiplied by average export	All values presented to NIE Networks for approval and validation
7	Apportionment of generation by voltage level and network type	○ Apportionment based on an assessment of sizes of generators with larger generators connected at higher voltage levels ○ Generator sizes and capacities for future connections taken from scenarios derived by Element Energy as part of the project	Checked by EA Technology against rationale used in GB for validity
8	Number of days used in the model to represent different times of year	○ 3 days (winter average, winter peak, summer average) to allow the study of different conditions ○ Aligned with previous GB work that was agreed with the DNO community	Checked by EA Technology against data from SONI for total demand levels
9	Feeder composition – number and types of customers per feeder	○ Based on sample data for LV circuits provided by NIE Networks ○ Various feeder customer compositions were then derived from this data and reconciled against total number of customers (supplied by NIE Networks)	All values presented to NIE Networks for approval and validation
10	Apportionment of feeder demand (high, medium and low) and distribution shape	○ Northern Ireland model uses average as base-case ○ Normally distributed demand about an average case can be applied (e.g. three cases where demand is 1x 0.8x and 1.2x the normal demand)	Apportionment checked by EA Technology and overall demand validated against SONI figures
11	Underlying load growth and energy efficiency assumptions into the future	○ Assumptions have been taken regarding the organic load growth (non-LCT) and increasing energy efficiency that give a small increase in load year on year to reflect the fact that these factors almost cancel each other out ○ Underlying load growth level of 0.7% p.a. used in line with process in GB to reflect the baseline from which LCTYs are connecting in a given year	Underlying load growth rate agreed between EA Technology and NIE Networks, which was then checked by EA Technology to ensure it does not trigger any reinforcement so as to avoid double counting.
12	Load that is amenable to DSR	○ Heating and LCT load types have an assessment of when they can be moved from and to in half-hourly blocks across the day	All data in alignment with GB and verified by EA Technology
13	Roll off of electric heating and economy 7 type	○ 25% roll off for electric heating for every HP deployed (i.e. 1 in 4 HP deployments go into houses previously on electric heating)	All data in alignment with GB and verified by EA Technology

	Parameter	Data Source	Checking process
	(storage heating) with the uptake of heat pumps	○ Until a limit of 50% (i.e. 50% of 2016 electric heating load continues until the end of the 2060 period)	
14	Northern Ireland input data scenarios	○ Data has been taken from a range of public sources such as DETI and ecarNI, DECC and OLEV ○ The same methodologies as used in GB were applied, but based on Northern Ireland specific parameters	Element Energy derived the scenarios based on the same method as they used in GB, with all figures being provide to NIE Networks for validation
15	Growth in LCT from 2030-2060	○ Public data generally stops at 2030 ○ Extrapolation has been undertaken (Element Energy) to expand the dataset out to 2060 using the same method as applied in GB	Element Energy derived the scenarios based on the same method as they used in GB, with all figures being provide to NIE Networks for validation
16	Size / number of all LCTs per installation and their fault level contribution	○ All based on 1 ‘unit’ per household for EVs ○ Allowance made for up to 2 HP units for larger /older houses ○ Allowance made for up to 4kW PV per house ○ Fault level contribution for all LCTs is set to zero as a default, owing to the fact that it is envisaged they will be connected via power electronics	As per the GB model with figures checked by EA Technology
17	Profile of EVs installations	○ Based on trial data from the Low Carbon Network Fund Tier 2 project: Low Carbon London	Checked against raw data by EA Technology
18	Profile of PV installations	○ PV data based on real installations in Kew testbed	Taken directly from the GB model and checked against that dataset by EA Technology
19	Profile of HP installations	○ Based on trial data from Low Carbon Network Fund projects	Taken directly from the GB model and checked against that dataset by EA Technology
20	Clustering of LCTs	○ All based on PV and FiT data observed in GB ○ Sensitivities run for no clustering and high clustering	Taken directly from the GB model and checked against that dataset by EA Technology

	Parameter	Data Source	Checking process
21	Apportionment of LCTs to feeders	○ Calculated as per the approach taken in GB whereby the number of LCTs on a given feeder type is calculated based on number of customers connected to that feeder and also the type of customers (to determine the 'attractiveness' of the LCT)	Same algorithmic process used in GB applied to the revised feeder types for Northern Ireland and checked by EA Technology
22	Number of years for investment look-ahead	○ Set as default as 5 years ○ Sensitivities run based on 1 year and 8 years	Checked and validated by EA Technology
23	Investment trigger point (intervention thresholds)	○ Variable trigger points depending on the network type and existing planning standards ○ These were discussed with NIE Networks and agreed at a workshop	All values presented to NIE Networks for approval and validation
24	Cost of conventional solutions	○ Representative solutions agreed with after extensive consultation in GB with the DNO community ○ These costs were directly transposed to Northern Ireland with the only adjustments being for circuit lengths	Directly taken from GB but presented to NIE Networks for approval and validation
25	Cost of smart solutions	○ Representative Solutions agreed in GB after extensive dialogue with the DNO community ○ Data taken, where existing, from LCN Fund projects or IFI projects ○ Where no data has been available assumptions have been made ○ All data is a direct transposition from the extensive stakeholder engagement and data governance process used in GB	Directly taken from GB but presented to NIE Networks for approval and validation
26	Cost of enablers	○ All data is a direct transposition from the extensive stakeholder engagement and data governance process used in GB	Directly taken from GB but presented to NIE Networks for approval and validation
27	Linkage between enablers and smart solutions	○ Manually set based on engineering judgement of which solutions will require which enabler technologies ○ This was a direct transposition of the data from the extensive engagement process that was carried out in GB to define the solutions	Directly taken from GB and checked for validity by EA Technology
28	Merit order 'cost function' for conventional and smart solutions	○ Factors (e.g. flexibility, cross-networks benefit, disruption) discussed and agreed with the GB DNO community ○ Assumptions made around the cost of these factors	Directly taken from GB and checked for validity by EA Technology

	Parameter	Data Source	Checking process
		○ Formula discussed with GB DNO community and directly transposed for Northern Ireland model	
29	Merit order settings per Variant Solution	○ Data in GB based on experience from trials and on extensive engagement with the DNO community ○ This was directly transposed to the Northern Ireland model	Directly taken from GB and checked for validity by EA Technology
30	Headroom release data for conventional and smart solutions	○ Data in GB based on experience from trials and on extensive engagement with the DNO community ○ This was directly transposed to the Northern Ireland model	Directly taken from GB and checked for validity by EA Technology
31	Availability of solutions (by year)	○ The availability of all solutions and enablers was discussed ta a workshop with NIE Networks ○ Appropriate years were selected to represent when the technologies are likely to be available to NIE Networks in an ‘off-the-shelf’ manner	All values presented to NIE Networks for approval and validation
32	Combinations of solutions (how many in a given year, which combinations are feasible)	○ Up to 5 solutions can be applied in parallel in the Transform Model ○ The feasible combinations of Variant Solutions have been tagged in the model and these are based on GB experience and directly transposed to Northern Ireland	Directly taken from GB and checked for validity by EA Technology
33	Life expectancy of solutions	○ Based on estimates of typical assets ○ This data is taken directly from the GB engagement with the DNO community and transposed to the Northern Ireland model	Directly taken from GB and checked for validity by EA Technology
34	Losses attributable to solutions	○ Based on engineering judgement relating to whether solutions will, for example, increase load on an asset (and therefore variable losses) ○ This data is taken directly from the GB engagement with the DNO community and transposed to the Northern Ireland model	Directly taken from GB and checked for validity by EA Technology
35	Quality of supply benefits attributable to solutions	○ Assessment based on engineering judgement regarding the positive or negative effect that the solution will have on CIs and CMLs ○ This data is taken directly from the GB engagement with the DNO community and transposed to the Northern Ireland model	Directly taken from GB and checked for validity by EA Technology
36	Nationally-driven DSR – payments to customers	○ Set as 10p/kWh as a default	Directly taken from GB and checked for validity by EA Technology

	Parameter	Data Source	Checking process
		○ This is not used in the calculation as it is only concerned with balancing demand at a national scale against generation and looking at supplier-led DSR	
37	Output costs	○ Only totex cost, for each year of the model ○ No disruption costs are brought out of the model	Directly taken from GB and checked for validity by EA Technology
38	Discount rate in model	○ Set to 3.5% until 2045 and then 3% beyond that in line with the Social Time Preference Rate	Directly taken from GB and checked for validity by EA Technology
39	Optimism bias for conventional and smart capex and all opex	○ Aligned with UK Government guidelines optimism bias is applied to all solutions and enablers in the model ○ Data in GB based on extensive engagement with the DNO community to determine the level of maturity of different approaches ○ The more mature the technology, the lower the optimism bias ○ This was directly transposed to the Northern Ireland model	Directly taken from GB and checked for validity by EA Technology

Appendix II Conventional Engineering Solutions

Conventional solutions refer to technological network solutions that are widely used in the design, operation and management of the current networks such as traditional reinforcement options. The conventional solution sets included in the Transform Model for the development of smart grids are presented in Table 13, Subsection 5.3. This appendix further expands Table 13 by providing a detailed description of each conventional solution set.

In the following diagrams any red coloured circuits or transformers indicate new assets deployed by the conventional solution under consideration. It should be stressed that the diagrams refer to the LV implementation of the conventional solutions, however, these are also applicable at HV and EHV as described in Subsection 5.3.

Split feeder

The split feeder conventional solution involves transferring half of the load of the existing feeder onto a new feeder.

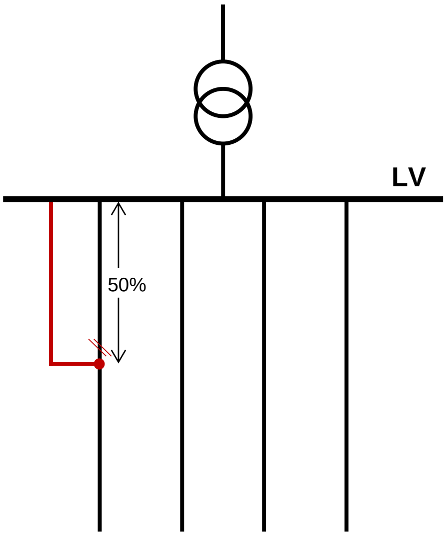

Figure 39 Split feeder

New split feeder

The new split feeder conventional solution includes running a new feeder from the substation to the midpoint of the already split feeder and perform some cable jointing to further split the load, resulting in three feeders each having approximately equal loads.

It should be noted that the total amount of cabling required to deliver this solution has been calculated to be equal to the cabling required to deliver the “split feeder” solution, but there is additional cross-jointing required meaning that the costs are slightly higher. Figure 40 indicates that 33% of the load now exists on each feeder in contrast to an unreinforced case. Note that the 33% figures are not representative of the relative cable lengths of each feeder.

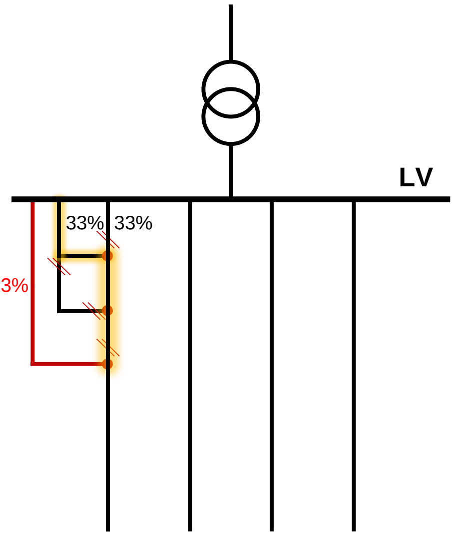

Figure 40 **New split feeder**

Replace transformer

The new transformer conventional solution includes the addition of a new transformer providing additional capacity and voltage support.

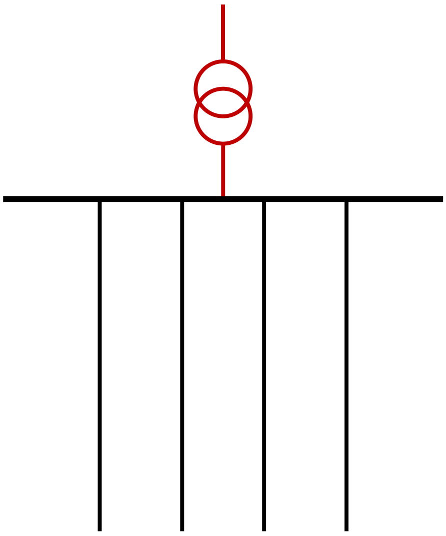

Figure 41 **Replace transformer**

Minor works

The minor works conventional solution considers the construction of one complete new substation electrically adjacent to an area experiencing headroom constraints. At LV this would involve the installation of a new pole mounted or pad mounted substation to take half of the load from the substation being reinforced but with limited HV cabling required, while at HV and EHV it will take the form of an additional transformer being installed at an existing site.

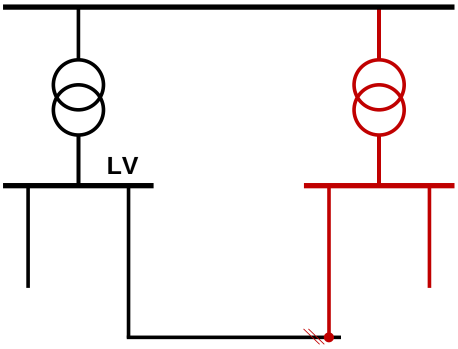

Figure 42 **Minor works**

Major works

The major works conventional solution involves the construction of new distribution transformer and circuits into an area where demand cannot be satisfied by simply ‘tweaking’ existing network infrastructure. At LV this would involve the construction of new distribution substations with associated LV cabling to integrate these substations into the heavily loaded network, and also some HV cabling to allow the new substations to be fed from the relevant primary substations; at higher voltages the principle is the same, with the construction of a new primary substation or bulk supply point and associated cabling.

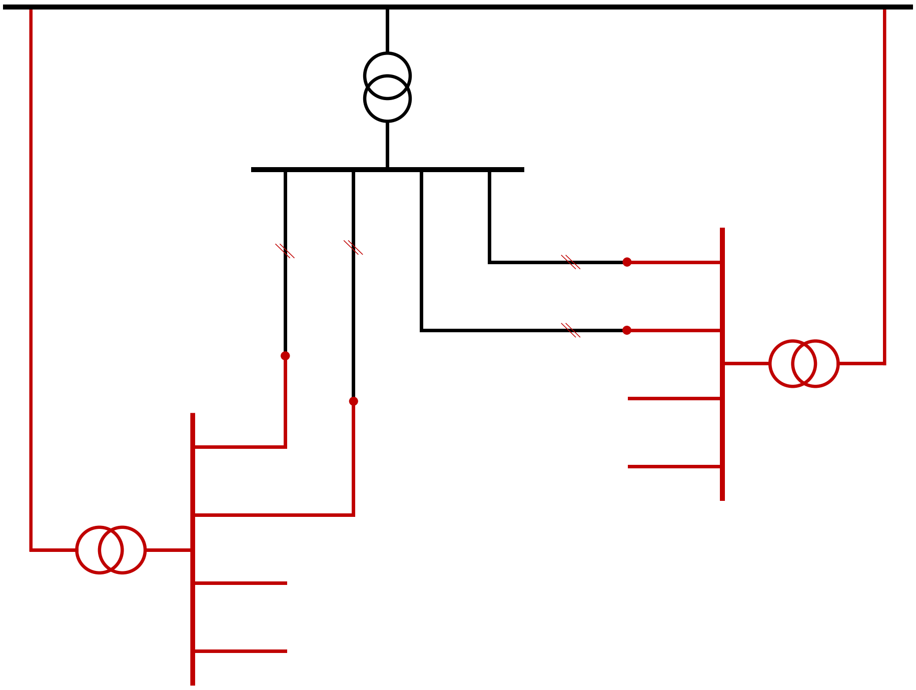

Figure 43 **Major works**

Appendix III Low Carbon Technology Demand Profiles

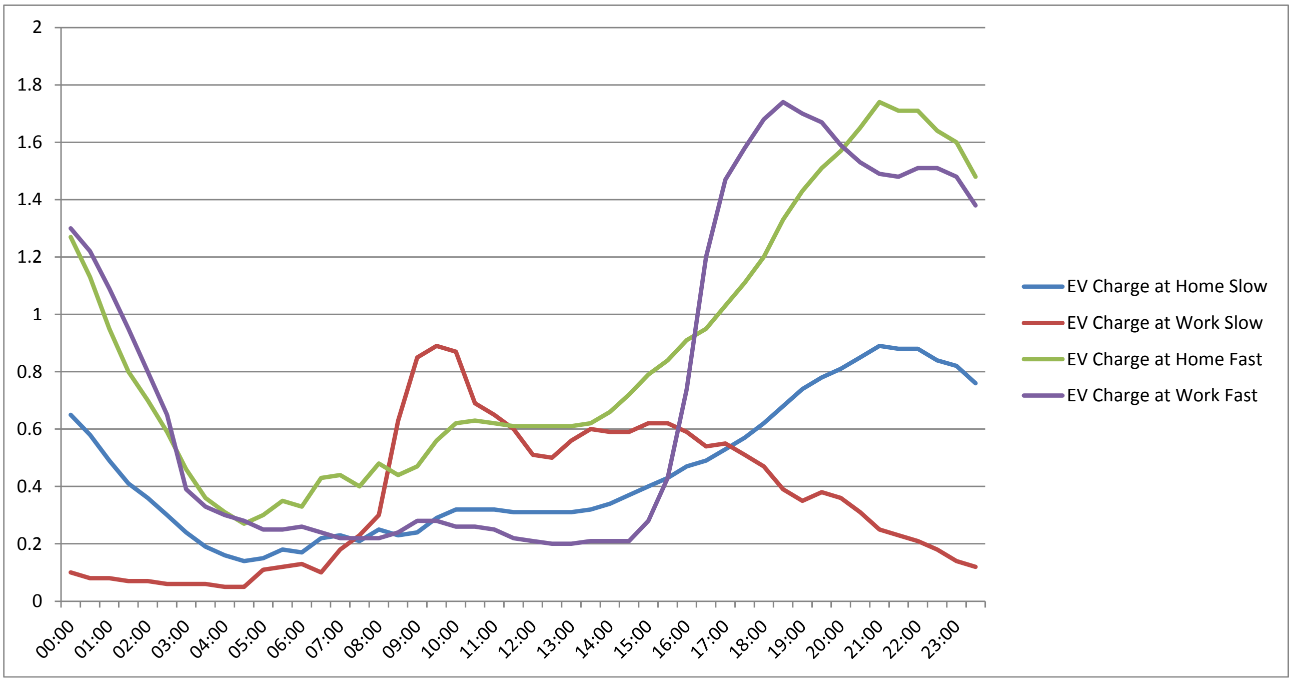

Figure 44 **Electric vehicle charging profiles**

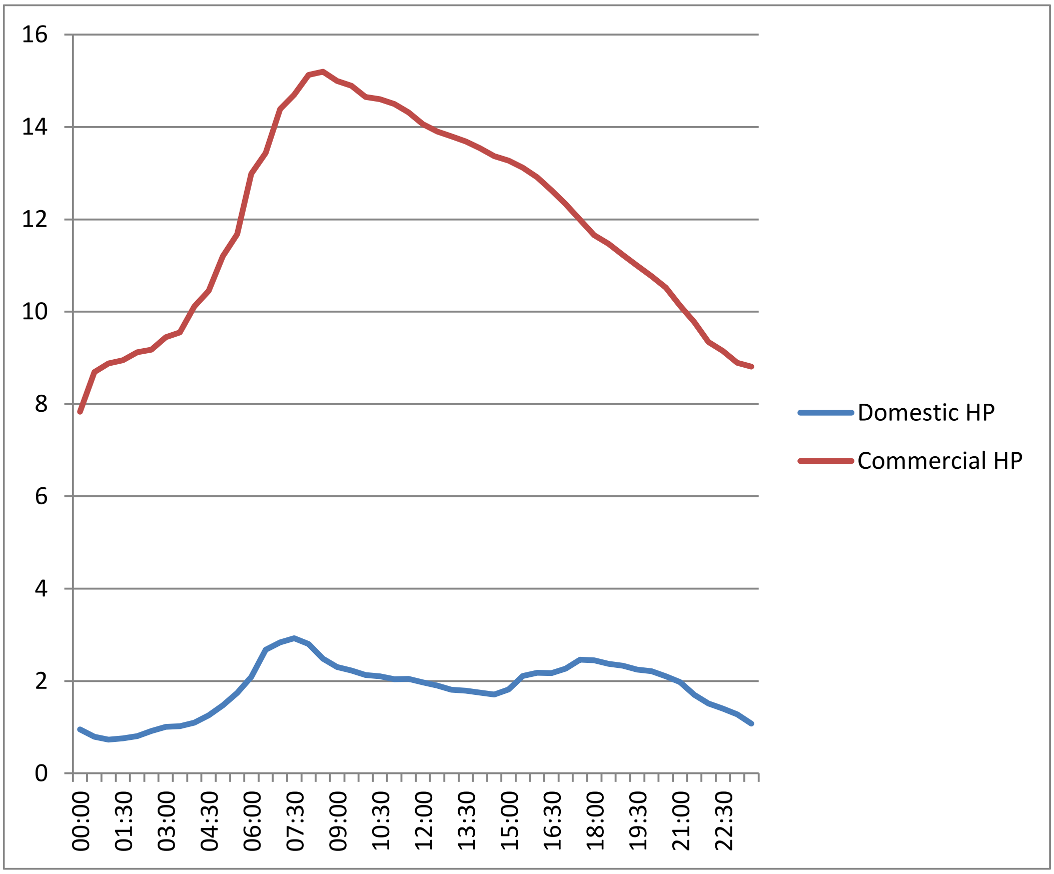

Figure 45 **Heat pump demand profiles**

Appendix IV Merit Order Cost Calculation

As described in the main document, the merit order cost for each solution is calculated via the following formula:

$$Solution\ Merit\ Cost = Flexibility \times \left(\frac{n}{Life\ Expectancy}\right) \times (TOTEX + Disruption + Cross\ Networks\ Benefits)$$

This section illustrates the example calculation of the merit order cost for two solutions: a conventional solution (new small primary transformer) and a smart solution (dynamic rating of an existing primary transformer).

Taking the conventional approach first, the solution has a capex cost of £115,825 per feeder that the transformer supplies. The annual opex associated with this is £1,158 and the life expectancy is 45 years. Both capex and opex are increased by 10% to allow for optimism bias, in line with recognised practice.

The totex of this solution is then calculated as the capex plus the NPV of the opex over the life of the asset and hence this is found to be £156,069.

The flexibility factor ascribed to this solution is 2 meaning that the cost should be multiplied by 95%. The disruption factor is 3 (fairly disruptive) meaning that a cost of £10,000 is allocated here. The cross network benefits factor is 0 and hence no additional factor is required here. Finally, the look-ahead period, n, is selected as a default to be 5 years. Thus substituting these values into the above equation gives a merit cost of £17,529.

Conversely, looking at the dynamic rating of a primary transformer, the capex is £41,320 with an annual opex of £4,132 and a life expectancy of 15 years. Both capex and opex are increased by 30% to reflect the greater uncertainty surrounding this solution than its conventional counterpart.

The totex is then calculated as the capex plus the NPV of the opex over the life of the solution and found to be £115,583.

The flexibility factor ascribed to this solution is 4 meaning that the cost should be multiplied by 85%. The disruption factor is 2 (low disruption) meaning that a cost of £2,500 is allocated here. The cross network benefits factor is 0 and hence no additional factor is required here. Finally, the look-ahead period, n, remains as a default to be 5 years. Thus substituting these values into the above equation gives a merit cost of £33,457; higher than the new asset owing to its shorter asset life, reflecting the fact that even though it is lower cost than the conventional asset, it will need to be replaced in 15 years, meaning that when looked at over the longer term, it represents a more expensive option.

Appendix V Network Details

Feeder	Average Capacity rating of upstream transformer (kVA)	Average number of upstream transformers at the upstream substation	Average capacity rating of upstream substation (kVA)	Average number of feeders out of the upstream substation	Average capacity ratingof upstream substation per feeder (kVA)	Average capacity rating of feeder (kVA)	Phase imbalance factor for substation (%)	Phase imbalance factor for feeder (%)	Thermal substation intervention threshold (%)	Thermal feeder intervention threshold (%)	De-rated average capacity rating of upstream substation per feeder (kVA)	De-rated average capacity rating of feeder (kVA)
EHV1 Urban Underground Radial	90,000	2	180,000	1	180,000	30,000	1	1	50%	50%	90,000	15,000
EHV2 Urban Underground Meshed	90,000	2	180,000	1	180,000	34,200	1	1	50%	60%	90,000	20,520
EHV3 Rural Mixed Radial	60,000	2	120,000	1	120,000	16,200	1	1	50%	50%	60,000	8,100
EHV4 Rural Mixed Meshed	60,000	2	120,000	1	120,000	19,500	1	1	50%	60%	60,000	11,700
HV1 Town Centre 11kV	15,000	2	30,000	10	3,000	5,620	1	1	65%	60%	1,950	3,372
HV2 Town Centre 6.6kV	15,000	2	30,000	8	3,750	5,200	1	1	65%	60%	2,438	3,120
HV3 Suburban UG 11kV	12,500	2	25,000	6	4,167	5,620	1	1	65%	60%	2,708	3,372
HV4 Suburban UG 6.6kV	12,500	2	25,000	8	3,125	5,200	1	1	65%	60%	2,031	3,120
HV5 Mixed 11kV	12,500	2	25,000	5	5,000	5,620	1	1	65%	60%	3,250	3,372
HV6 Mixed/Rural 6.6kV	10,000	2	20,000	5	4,000	2,457	1	1	65%	60%	2,600	1,474
HV7 Rural OH 11kV	5,000	2	10,000	4	2,500	3,523	1	1	65%	60%	1,625	2,114
HV8 Single Transformer Primary 11kV	6,250	1	6,250	3	2,083	3,523	1	1	65%	60%	1,354	2,114
LV1 Belfast city (Commercial)	1,000	1	1,000	8	125	162	0.9	0.9	130%	100%	146	146
LV2 Dense Urban (apartments etc)	500	1	500	5	100	205	0.9	0.9	130%	100%	117	185
LV3 Town Centre	500	1	500	5	100	162	0.9	0.9	130%	100%	117	146
LV4 Industrial estate	500	1	500	3	167	205	0.9	0.9	130%	100%	195	185
LV5 Retail park	500	1	500	6	83.33	205	0.9	0.9	130%	100%	98	185
LV6 Housing pre 1990s (3-4 bed semi-detached and detached)	500	1	500	5	100	140	0.9	0.9	130%	100%	117	126
LV7 New build housing estate	315	1	315	4	79	205	0.9	0.9	130%	100%	92	185
LV8 Terraced street	800	1	800	7	114	140	0.9	0.9	130%	100%	134	126
LV9 Single dwelling	16	1	16	1	16	18	0.9	0.9	130%	100%	19	16
LV10 Large farms	50	1	50	1	50	80	0.9	0.9	130%	100%	59	72
LV11 Rural hamlet	100	1	100	1	100	125	0.9	0.9	130%	100%	117	113
LV12 Generator export	1,000	1	1,000	1	1,000	500	1	1	130%	100%	1,300	500
LV13 2-3 dwellings	25	1	25	1	25	80	0.9	0.9	130%	100%	29	72
LV14 Other terraced	500	1	500	6	83	205	0.9	0.9	130%	100%	98	185
LV15 Town Centre (Light)	500	1	500	5	100	162	0.9	0.9	130%	100%	117	146
LV16 Housing pre 1990s (Light)	500	1	500	5	100	140	0.9	0.9	130%	100%	117	126
LV17 Other Terraced (Light)	500	1	500	6	83	205	0.9	0.9	130%	100%	98	185

Feeder	Lower voltage intervention threshold (%)	Upper voltage intervention threshold (%)	Magnitude of load producing 1% voltage drop (kVA)	Network fault level (MVA)	Fault level intervention threshold (MVA)	Variable losses (%)	Fixed losses (kVA)	Number of GMTs on feeder downstream	Number of PMTs on feeder downstream	Average Feeds per GMT	Average Feeds per PMT	Number of Feeders Supplied	Number of networks
EHV1 Urban Underground Radial	6%	4%	19,300	563	750	0.19%	-	1	-	9	-	9	21
EHV2 Urban Underground Meshed	6%	4%	18,000	713	750	0.15%	-	1	-	9	-	9	21
EHV3 Rural Mixed Radial	6%	4%	7,700	388	750	0.59%	-	1	-	4	-	4	125
EHV4 Rural Mixed Meshed	6%	4%	8,600	538	750	0.25%	-	1	-	4	-	4	98
HV1 Town Centre 11kV	6%	3%	1,500	130	250	0.65%	12,264	9	-	3	-	27	255
HV2 Town Centre 6.6kV	6%	3%	600	88	150	0.47%	21,900	6	-	4	-	24	105
HV3 Suburban UG 11kV	6%	3%	1,500	130	250	0.60%	13,140	9	-	3	-	27	276
HV4 Suburban UG 6.6kV	6%	3%	600	88	150	3.17%	14,016	6	-	4	-	24	226
HV5 Mixed 11kV	6%	3%	1,500	130	250	7.56%	11,680	6	158	3	1	176	136
HV6 Mixed/Rural 6.6kV	6%	3%	500	75	150	8.61%	11,680	7	17	3	1	38	18
HV7 Rural OH 11kV	6%	3%	280	75	250	1.00%	-	-	180	-	1	180	167
HV8 Single Transformer Primary 11kV	6%	3%	280	75	250	1.00%	-	-	180	-	1	180	87
LV1 Belfast city (Commercial)	6%	10%	40	5	25	4.28%	584						427
LV2 Dense Urban (apartments etc)	6%	10%	35	4	25	1.32%	701						428
LV3 Town Centre	6%	10%	40	5	25	6.63%	631						3,473
LV4 Industrial estate	6%	10%	35	5	25	3.00%	1,051						860
LV5 Retail park	6%	10%	35	5	25	2.45%	1,051						851
LV6 Housing pre 1990s (3-4 bed semi-detached and detached)	6%	10%	35	4	25	3.69%	526						8,617
LV7 New build housing estate	6%	10%	30	4	25	1.10%	526						3,986
LV8 Terraced street	6%	10%	35	4	25	3.01%	526						858
LV9 Single dwelling	6%	10%	10	3	25	4.80%	140						25,645
LV10 Large farms	6%	10%	10	3	25	4.80%	140						4,796
LV11 Rural hamlet	6%	10%	15	3	25	4.80%	140						2,146
LV12 Generator export	6%	10%	40	10	25	0.00%	-						300
LV13 2-3 dwellings	6%	10%	10	3	25	2.49%	350						21,587
LV14 Other terraced	6%	10%	30	4	25	3.01%	526						4,236
LV15 Town Centre (Light)	6%	10%	40	5	25	6.63%	631						1,612
LV16 Housing pre 1990s (Light)	6%	10%	35	4	25	3.69%	526						8,562
LV17 Other Terraced (Light)	6%	10%	30	4	25	3.01%	526						4,246

Global Footprint

We provide products, services and support for customers in 90 countries, through our offices in Australia, China, Europe, Singapore, UAE and USA, together with more than 40 distribution partners.

Our Expertise

We provide world-leading asset management solutions for power plant and networks.

Our customers include electricity generation, transmission and distribution companies, together with major power plant operators in the private and public sectors.

- Our products, services, management systems and knowledge enable customers to:
- Prevent outages
- Assess the condition of assets
- Understand why assets fail
- Optimise network operations
- Make smarter investment decisions
- Build smarter grids
- Achieve the latest standards
- Develop their power skills