Programme Area: Light Duty Vehicles

Project: Electricity Distribution and Intelligent Infrastructure

Title: Electricity Distribution Network Assessment and Analysis

Abstract:

This project was undertaken and delivered prior to 2012, the results of this project were correct at the time of publication and may contain, or be based on, information or assumptions which have subsequently changed. This report provides an analysis of the impact of plug-in vehicle recharging on the UK electricity distribution system against a range of vehicle uptake and recharging profile scenarios. The key finding is that moderate uptake of plug-in vehicles could cause significant challenges for distribution networks, if demand from recharging is uncontrolled. The constraints arise largely from voltage drop and unbalance, violation of transformer and cable thermal limits, increases in network losses, fault levels and issues such as harmonics and step voltage changes. Traditional network reinforcement, by way of substation upgrades and cable reinforcement, is likely to be increasingly inefficient in terms of accommodating the incremental and unpredictable loads expected from plug-in vehicles and heat-pumps. If uptake is expected to be significant, a 'smart grid' approach is recommended.

Context:

This project looked at the potential impact of electric vehicles on the UK electricity distribution grid.

Cover Page

Deliverable Title	Electricity Distribution Network Assessment and Analysis Final Report
Deliverable Reference	SP2/EDFEN/04_v.2.1

Interim or Final	Final

Original Due Date	17/02/11
Submission Date	15/04/11

Author	Sara Bell, UK Power Networks
Author	Nick Heyward, UK Power Networks
Author	Pavlos Trichakis, formerly UK Power Networks
Contributing Organisations	Imperial, EDF R&D, IBM and E.ON

Approvers	UK Power Networks

Version	**History**
v.1.0	Initial Submission (15/04/11)
v.2.0	Updates and addition of references, glossary
v.2.1	Figure and table numbering corrected

IP Ownership	No IP Contained within this Deliverable

Table of Contents

Tables

Figures

Executive Summary

The ETI's Plug-in Vehicle (PiV) Economics and Infrastructure Project forms part of 'Test Bed UK', which is the overall approach to prepare, plan and design the systems and infrastructure that will enable and encourage the widespread adoption of plug-in vehicles in the United Kingdom (UK) market. The Electricity Distribution and Intelligent Infrastructure Project considers the impacts and inter-relationships of vehicle recharging on electricity distribution networks and the intelligent information infrastructure needed to facilitate it. This report pulls together the work of UK Power Networks (formerly EDF Energy Networks), EDF R&D and Imperial Consultants and refers to work by the wider project consortium including IBM and E.ON. The objective of this report is to explain what the impacts on distribution networks will be and consider the methods for mitigating the impacts and the associated costs of that mitigation. The report considers a time horizon to 2050 in discussing both likely PiV uptake scenarios and their resultant implications for the distribution network.

Moderate uptake of PiVs could cause significant challenges for distribution networks if demand from recharging is uncontrolled. Constraints arise largely from voltage drop and unbalance, violation of transformer and cable thermal limits, increases in network losses, fault levels and issues such as harmonics and step voltage changes. However, the level of reinforcement required to accommodate PiV demand will vary by distribution network type, for example urban versus rural networks, due to a range of factors such as differing technical design characteristics, levels of expected PiV penetration, customer behaviour and adoption of time-of-use tariffs.

Traditional network reinforcement, by way of substation upgrades and cable reinforcement, is likely to be increasingly inefficient in terms of accommodating the incremental and unpredictable loads expected from PiVs and heat-pumps. Further, the costs of traditional reinforcement are likely to be significantly greater compared to the capital expenditure and operational costs required to build and maintain 'intelligent infrastructure' to enable more controlled, smart PiV recharging.

Hence, if future electrical distribution networks are to realise their full potential in order to support the challenges associated with the transition to low-carbon electricity, Distribution Network Operators (DNOs) will need to move away from the conventional, passive reinforcement approach towards a 'smart grid' approach encompassing a higher degree of network operational management.

In addition to network management measures such as LV voltage control, implementation of 'customer-side' mitigation strategies or DSM will play a key part in the smart grid approach. It is estimated that overall, the net present value (NPV) of national network reinforcement by DNOs can potentially be reduced over 2010-2050 from around £6 billion (NPV) down to £1.5 billion (NPV) by such demand-side measures, depending on the level of system intelligence implemented. However, the success of such measures and the effectiveness of a smart grid are also reliant on effective consumer engagement, the costs of which are challenging to forecast.

1 Introduction

The electricity grid is a collection of large, centralised and smaller distributed power stations and transmission and distribution electrical infrastructure that generate and deliver electrical energy to end customers. At present, electrical energy cannot be economically stored in large quantities; therefore the production and consumption of electricity must take place in real time. During recent years, the electricity grid in GB has evolved in order to meet the dynamically changing electricity demand by employing a range of power plant types which carry out various roles in the overall grid operation. Each type of power plant is typically of a different rating capacity and may employ different technologies and energy resources, which results in different cost and emission characteristics. Base-load power plants, such as large coal, nuclear and Combined Cycle Gas Turbine (CCGT) plants in the UK, were designed to continuously operate at a minimum cost, while peak-load power plants, such as gas turbine, storage and pumped storage plants, are more costly to operate and are operated only when system demand is at its highest levels. In addition, some other power plant types can be thought of as operating in between, such as wind turbines and photovoltaic solar panels.

This will be a challenging task as it will involve replacing large flexible fossil fuelled generators with a large number of small, often less controllable, power generation sources each of whom may have an individual commercial contract for supply. Hence, sufficient reserve margins will be required in order to dynamically manage the balance between generation and demand, with Demand Side Management (DSM) and Electrical Energy Storage Management (ESM) schemes also likely to be employed. This is because without the contribution of DG (Distribution Generation), DSM and ESM schemes into the system operation activities, a larger proportion of conventional large-scale generation plants will have to be retained as system reserve, leading to increasingly uneconomic solutions to mitigate the impact of a large percentage of clean but inflexible generation in the system.

The report commences with an examination of the future of distribution networks in the UK in Chapter 2. This chapter looks at policy initiatives such as the UK Smart Metering Roadmap and the UK Smart Grids Roadmap and their implications for distribution networks. The development of a Smart Grid that interfaces with PiV chargers and is integrated with the existing smart metering infrastructure will bring together electricity companies (power generation, transmission, distribution and retailers), IT companies, technology and service providers, local authorities and car park operators with the PiV industry, ultimately creating a new mobile load on the network.

The amount of network reinforcement that will be required to accommodate this new demand will depend on the timing, location, duration and amount of load added, which in turn will depend on a number of factors such as individual customer behaviour, electricity tariffs and PiV uptake rates. DNOs will require greater monitoring, and potentially control, of the power requirements in those areas with a high penetration of PiVs in order to ensure that security and quality of supply is not degraded. This is because the ability to better monitor and manage electricity consumption patterns, as well as improving the efficiency with which the distribution network is operating could minimise the expansion and reinforcement required.

Traditionally, electricity distribution networks in GB have been designed and operated based on moderate annual load growth scenarios. PiVs represent a new type of load which is different compared to some of the traditional electrical loads due to the highly mobile and unpredictable nature of PiVs. Chapter 3 looks at the challenges and constraints of widespread uptake of PiVs and the implications for network design and operation for this load growth.

Chapters 4 and 5 focus on the costs of network reinforcement and intelligent infrastructure. This sets the scene for the investment required to achieve the network reinforcement savings identified through the Imperial Consultant's model. In order to ensure fully smart recharging of PiVs and thereby avoid reinforcement by ensuring that existing demand peaks are not exacerbated by indiscriminate recharging, significant investment is required in upgrading substations and creating an intelligent infrastructure to manage PiV load. This report recognises that some investment will be made in the course of moving to a smart grid environment and that this investment will benefit PiV owners as well as the wider electricity using community. The purpose of this report is not to cost a smart grid but rather to attempt to cost specific aspects of smart grid infrastructure that will be needed for smart PiV recharging.

Chapter 6 explains Demand Side Management (DSM) and gives some scenarios to demonstrate the benefits of DSM. The network reinforcement cost scenarios make assumptions that PiV owners will be prepared to participate in smart recharging. This chapter explains how this consumer acceptance and involvement might be achieved through commercial measures of financially rewarding smart recharging.

Chapter 7 describes the Network Model constructed by Imperial Consultants to evaluate the cost of network reinforcement as a result of widespread uptake of PiVs. The chapter describes the components of the model and how these have been built up to arrive at a model that shows the distribution network of Great Britain in a representative manner.

Finally, Chapter 8 shows scenarios of network reinforcement cost as a result of varying inputs into the model. Imperial Consultants have carried out a wide range of sensitivity studies to explore the scope and benefits of a number of options to mitigate the impact of PiV uptake on distribution networks. The developed modelling capability has been employed to analyse alternative network reinforcement schemes, PiV recharging optimisation, voltage control, application of smart appliances and Heat Pump (HP) storage optimization. The report concludes by drawing together all chapters and giving recommendations for how this report can be used to inform policy frameworks.

2 The Future of UK Distribution Networks

During recent years, fears over global warming, high oil prices, the decline of indigenous energy supplies and increasing Governmental support have led to a continuous increase in electrical energy being produced by generators based on renewable energy sources. Furthermore, the deregulation of the electricity industry has also played a key role in increasing competition and thus allowing more privately owned generators to be connected to the distribution system. The anticipated increase in Distributed Generation (DG) will require the connection of large numbers of generators at a part of the system that has not been designed with DG in mind. In addition, Small Scale Embedded Generators (SSEGs) installed at end users' premises at LV levels are also gaining momentum, in particular as a result of the introduction of Feed-in-Tariffs from April 2010. The anticipated increase in DG and SSEG may reverse the power flows within electrical distribution networks, which could have serious technical impacts in the way these electrical systems are designed and operated.

Moreover, the introduction of intermittent generation (such as generators powered by renewable energy sources) as well as 'clean' but inflexible large-scale generation such as nuclear and Carbon Capture and Storage (CCS) power plants brings in a higher level of uncertainty and thus raises challenging technical questions with regards to power system operation and security of supply. In particular, the fact that DG is not usually dispatched by the network operator has meant that existing techniques and practices have had to be reviewed and updated to take these features into account. Compared to large centralised generation power plants, DG and SSEG units generally have a lower capacity factor, i.e. a higher ratio of peak to average generation. This is either due to the intermittent nature of their primary energy source in the case of renewables or due to operational and economical constraints such as the heat-bound limitations of Combined Heat and Power (CHP) plants.

If the potential benefits of employing zero or low carbon generators are to be realised, their growth must be accompanied by some phased decommissioning of large centralised plants without resulting in a reduction in security of supply. This will be a challenging task as it will involve replacing large, flexible fossil fuelled generators with a large number of small, often less controllable, power generation sources each of whom may have an individual commercial contract for supply. Hence, sufficient reserve margins will be required in order to dynamically manage the balance between generation and demand, with Demand Side Management (DSM) and electrical Energy Storage Management (ESM) schemes also likely to be employed. This is because without the contribution of DG, DSM and ESM schemes, a larger proportion of conventional large-scale generation plants will have to be retained as system reserve, leading to increasingly uneconomic solutions to energy supply.

Additionally, as the UK moves closer to the near-zero carbon electricity system of 2050, emissions from households will need to be close to zero. This is anticipated to be achieved by energy efficiency measures, as well as by producing more heat from low-carbon sources. With the progressive fall in the carbon intensity of electrical power generation in the UK, an important low carbon alternative will be the electrification of heating and cooling. A move away from gas boilers towards ground- and air-source heat pumps powered by electrical energy may therefore become increasingly common. However, that would result in an increase in the overall UK electricity demand, as well as a need to increase the generating capacity to meet that demand. Additionally, a move towards plug-in hybrids and fully electric vehicles (PiVs) could place significant additional power demands on the electricity grid which may require significant investments in grid expansion and/or grid reinforcement. The amount of infrastructure reinforcement that will be required to accommodate this demand will depend on the timing, location, duration and amount of load added, which in turn will depend on a number of factors such as individual customer behaviour, electricity tariffs and PiV uptake rates. DNOs will require greater monitoring, and potentially control, of the power requirements in those areas with a high penetration of PiVs in order to ensure that security and quality of supply is not degraded. This is because the ability to better monitor and manage electricity consumption patterns, as well as improving the efficiency with which the distribution network is operating could minimise the expansion and reinforcement required.

2.1 The UK Smart Metering Roadmap

Responding to the twofold challenge of tackling climate change (by reducing greenhouse gas emissions and by promoting energy saving policies) as well as ensuring energy security, the UK Government announced in the 'UK Low Carbon Transition Plan' [1] that gas and electricity smart meters are to be rolled out by energy suppliers to every home in Britain by the end of 2020. Some 26 million electricity and 22 million gas meters will need to be fitted, which represents a £7-8bn private investment and one of the building blocks for creating a 'Smart Grid'. It is envisaged that smart meters will provide customers with real-time information about their energy use along with the price they are paying for it, encouraging them to act on energy efficiency advice and reduce their carbon emissions. Energy suppliers on the other hand will be able to offer improved services to their customers, such as a wider range of tariffs and incentive packages, and it is also anticipated by the Government that faster and smoother switching between energy suppliers may also be achieved. DNOs may also realise significant operational benefits through more efficient asset management practices and better informed investment decisions stemming from improved real-time monitoring of their networks. Finally, smart metering may facilitate the introduction and increased use of micro-generation and ultra low carbon vehicles (electric and plug-in hybrids), which in turn can potentially offer significant technical, economical and environmental benefits [2].

In May 2009, the UK Government published a 'Consultation on Smart Metering for Electricity and Gas' [3]. The purpose of this document was to confirm the shape and high-level requirements for the domestic roll-out, while at the same time setting out proposals to mandate a smart/advanced meter roll out for small and medium non-domestic sites. Following a reviewing process, the Government published in July 2010 a Prospectus containing proposals for the delivery of electricity and gas smart metering in the UK, representing the joint views of the Department of Energy and Climate Change (DECC) and the Gas and Electricity Markets Authority (GEMA). The Prospectus states that the Government wishes to see a significant acceleration of smart meter roll-out compared to previously published targets and estimates benefits of £17.8bn over the next 20 years, with a net benefit estimated at £7.2bn [4]. A staged approach to implementation is proposed under which the responsibility for purchasing and installing the meters falls to the energy suppliers and that: "*suppliers will start to install smart meters that meet the minimum requirements defined in common technical specifications ahead of a central data and communications entity (DataCommsCo or DCC) being established*". The brief notes, "*Ofgem will introduce license conditions into Suppliers' licenses to set targets for roll out that will include flexibility in the early stages to enable suppliers to respond to customer demand and learn from experience. In parallel, during the initial stages of roll-out, additional measures to increase the effectiveness of the rollout and secure the energy savings will be considered by Ofgem*" [4].

It is outside the purposes of this report to describe in detail each of these issues raised in the Prospectus, however the Government anticipates that within a customer's home or business the metering system will be made up of smart meters for gas and electricity, a Home Area Network (HAN) to communicate between devices in the home (or business), and Wide Area Network (WAN) equipment for communicating back to the supplier or other authorised parties. For domestic consumers, suppliers will also be required to provide an in-home display giving near real-time information on energy consumption in an easily understandable form. The Government's proposed design requirements for the different elements of the smart metering system can be found in the 'Statement of Design Requirements' [5], and it is compulsory that all smart meters must comply with a specific set of high-level functional requirements. Additionally, the Government has concluded that the Central Communications Model as illustrated in Figure 2-1, under which communications to and from the smart meter are co-ordinated centrally by a new, nationwide function (labelled 'DCC'), offers the best model for Britain's smart meter roll out.

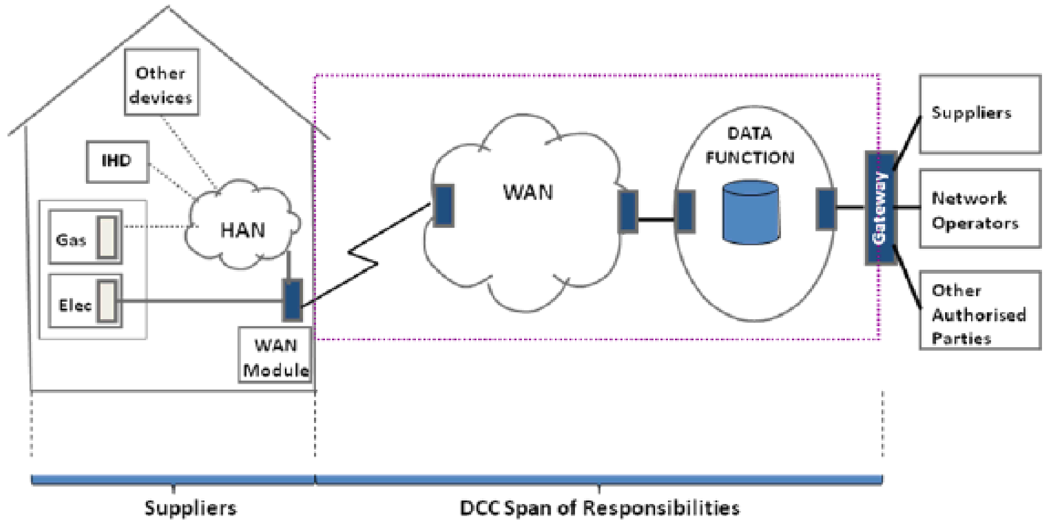


Figure 2-1: Proposed Smart Metering System Responsibilities [4]

The Government has recognised that successful delivery of the smart metering implementation programme, and hence realisation of the benefits case, will be dependent on "*active engagement with smart metering by consumers and on the active participation and commitment of a diverse range of stakeholders, including consumer groups, energy suppliers, meter manufacturers, installation companies and central industry bodies*" [4].

Two implementation strategies were considered:

1. 'Full establishment', where the mandated roll-out of smart meters would commence when the full smart metering regulatory regime and end-to-end system, including the DCC, has been established.
2. 'Staged implementation', where the set up of the DCC is removed from the critical path. Under this approach, confirmation of the meter technical specifications is expected to occur by winter 2011, with licence modifications mandating roll-out targets occurring in early 2012. Energy suppliers would be able to commence roll-out with certainty about the meter technical specifications, however to allow time for suppliers planning and procurement activities, mandated roll-out targets would only come into effect six months later, from summer 2012.

As noted earlier, the Government is determined to accelerate the roll-out of smart meters ahead of previously published plans. The staged implementation approach is expected to advance the start of the mandated roll-out by at least a year compared to the 'full establishment' approach, while maintaining the business case for the programme. For these reasons, the staged implementation approach is proposed by the UK Government [4]. Table 2-1 summarises the key milestone dates related to the smart metering implementation programme in the UK, with appropriate target profiles for roll-out being mandated by modifications to supply licences in early 2012 and becoming effective from summer 2012.

Date	Milestone
Spring 2011	Enhanced consumer protections introduced as required
Summer 2011	Functional requirements and technical specifications confirmed (subject, if required, to the outcome of any EU notification period)
Early 2012	Supply licence modifications mandating roll-out implemented
Spring 2012	Regulatory framework relating to DCC implemented
	Competitive application process for DCC licence
Summer 2012	Mandated supplier roll-out commences
Autumn 2012	DCC licence granted
Spring 2013	DCC service providers appointed
Autumn 2013	DCC trialling and testing complete
	Mandate use of DCC for domestic customers

Table 2-1: Proposed Key Milestones for The Smart Metering Implementation Programme [4]

2.2 The UK Smart Grids Roadmap

In the UK, support for the development of a Smart Grid [6] is being underlined by the Government's low-carbon strategy, as set out in the Low Carbon Transition Plan [1] and Renewable Energy Strategy [7], along with Ofgem's Low Carbon Network fund [9] and RPI-X@20 project [8]. The Low Carbon Network Fund is a funding mechanism of £500m over the period of 2010 to 2015 intended to support 'large-scale trials of advanced technology including smart grids' [9], as an important part of Distribution Pricing Control Review 5 (DPCR 5), the five yearly distribution price control review that Ofgem undertakes that establish incentives, revenues and expenditure allowed by UK DNOs. Moreover, RPI-X@20 was a two year project to review the current approach to UK energy network regulation and develop future policy recommendations [8]. The review looked at how best to regulate energy network companies to enable them to meet the challenges and opportunities of delivering the networks required for a sustainable, low carbon energy sector and in October 2010 published its 'Final Decision' document [10] to implement a new regulatory framework, known as the RIIO model (Revenue = Incentives + Innovation + Outputs).

The RIIO model has been designed to promote smarter gas and electricity networks for a low carbon future and will first be applied in the next transmission and gas distribution price control reviews (due to be implemented by April 2013) and in the sixth electricity distribution price control review. However, it is important to note here that, while uncertainty with regards to the smart metering roadmap in the UK has reduced considerably over the past two years as a result of the recent regulatory frameworks and ambitious penetration targets described in the previous section, there is still ambiguity with regards to the UK Smart Grid roadmap. It is likely that in the near future this will depend on the success of various research, development and demonstration projects currently planned under the Low Carbon Networks Fund and the Innovation Funding Incentive.

The UK Low Carbon Transition Plan [1] recognises the need for creating a "*bigger, smarter grid*" and identifies a smarter future grid as one of four key areas required in order to "*manage electricity generated from new technologies and respond to changes in energy demand".*

The 'Smart Grid Working Group' of the Electricity Networks Strategy Group (ENSG) produced in November 2009 a 'Smart Grid Vision' [11] and in February 2010 a 'Smart Grid Route Map' [12] as high level plans for delivering a UK smart grid. Additionally, the Working Group is currently undertaking a study on the costs, benefits and issues to be addressed in developing a UK smart grid, including technology readiness, how such a system might develop, and the drivers and barriers at each stage. Using the ENSG assessment and the Government's own analysis, the Government will publish its views on the actions required to deliver a smarter grid in the UK, as part of the roadmap for the whole energy system to 2050.

The 'Smart Grid Vision' [11] document defines a Smart Grid as an electrical network which employs communications, innovative products and services together with intelligent monitoring and control technologies to:

- Facilitate connection and operation of generators of all sizes and technologies.
- Enable the demand side to play a part in optimising the operation of the system.
- Extend system balancing into distribution and the home.
- Provide consumers with greater information and choice of supply.
- Significantly reduce the environmental impact of the total electricity supply system.
- Deliver required levels of reliability, flexibility, quality and security of supply.

The Smart Grid is seen by the ENSG as a key enabler to accommodate a number of critical developments that will take place in the future. These developments are illustrated in Figure 2-2 and can potentially play an important part to a low-carbon future.

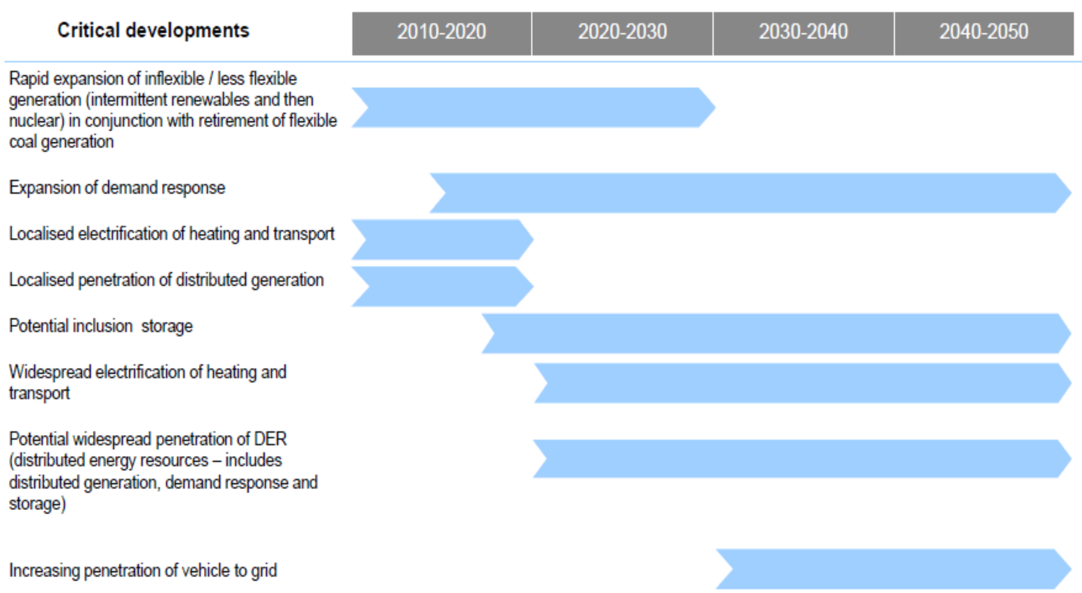


Figure 2-2: Timeline of the Critical Developments Anticipated to take place in the Electricity

Supply Industry [12]

According to the ENSG, for the successful delivery of a UK Smart Grid, four parameters will need to be addressed:

- Developing suitable regulatory and commercial arrangements.
- Building and expanding industry capabilities and capacity.
- Informing and involving customers to play an active role in the supply chain and security of supply.
- Trialling and proving integrated technology at scale.

The ENSG does not endorse any specific proposals in their roadmap on how the UK Smart Grid will be realised. Rather, they believe that it is critical to deliver a range of well targeted Research and Development (R&D) pilot projects between 2010 and 2015, funded through the Low Carbon Network Fund and the Innovation Funding Incentive, in conjunction with EU and private funding initiatives. Some of these R&D projects may then prove to be technically and economically successful and therefore available for nationwide employment after 2015. Additionally, the Smart Grid roadmap must respect the timeline for the smart metering implementation programme, as shown in Table 2-1, along with the uncertainty with regards to the precise nature of the UK's future end-to-end energy system, suggesting that the roadmap is likely to evolve over time.

2.3 Future Changes To UK Distribution Networks

The goal for the electrical distribution networks of the future is to achieve high levels of reliability, quality and security of supply, while at the same time helping to reduce the environmental impact of the total electricity supply and providing consumers with greater information and choice of supply. The future changes to the way UK electrical distribution networks are designed and operated will mainly depend on the new daily and seasonal load patterns that will be observed due to the additional electrical load that will be added to the distribution system (i.e. how much, when, where, for how long etc), along with the technologies that will be employed to increase distribution network capacity to acceptable levels. From a macro-level point of view, the additional load that will be added to the UK electricity system will depend on various factors, most of them linked to regional and national levels of economic activity, as well as future changes to the electricity sector.

These factors include:

- Gross Domestic Product (GDP) projections of the UK and local economies.
- Employment trends and projections for the UK and local economies.
- New-build trends and projections, which have been volatile and difficult to predict in recent times due to the turbulent economic climate.
- Scope for load growth in load building appliances, such as digital home electronics.
- Scope for load growth in electric vehicles, heat pumps and air-conditioning units.
- The change in future customer energy use behaviours, for example as a response to climate change concerns or through active market participation with their Smart Meters.
- The load growth offsetting impact of energy efficiency initiatives and more energy efficient appliances.
- The load growth offsetting impact of DG and micro-generation schemes, in particular due to the introduction of Feed-in-Tariffs from April 2010.
- The effect of growing competition in the provision of electricity connections.
- Regulatory and legislative changes and any other policy schemes that affect the level of connection charge for new connections.

The scope for load growth in PiVs and heat pumps is of particular interest as a recent report [13] indicated that at the national level, full penetration of PiVs and heat pumps could increase the present daily electricity consumption by about 50%, while doubling the system peak. Consequently, such an increase would result in a need to increase generation capacity along with significant investments in grid expansion and/or grid reinforcement. As far as PiV load growth is concerned, the uncertainty with regards potential PiV uptakes, as well as recharging and driving patterns make it inherently difficult to accurately quantify the additional demand that will be added and as such to provide estimates on the upgrade costs that could be required. From the DNO point of view, PiVs represent a new type of load which is different compared to some of the traditional electrical loads due to the highly mobile and unpredictable nature of PiVs. Additionally, predicting the demand that will be added to the system due to electrifying the heating and cooling sector is equally challenging. The amount of infrastructure reinforcement that will be required to accommodate this demand will depend on the timing, location, duration and amount of load added, which in turn will depend on a number of factors such as individual customer behaviour, electricity tariffs, PiV and heat pump uptake rates etc. Hence, as previously mentioned, DNOs will require greater monitoring, and potentially control, of the power requirements in those areas with a high penetration of PiVs and heat pumps in order to ensure that security and quality of supply is not degraded. This is because the ability to better monitor and manage electricity consumption patterns, as well as to improve the efficiency with which the distribution network is operating, could minimise the expansion and reinforcement required.

As a result of electrification of the transport and heating sectors, it is likely that DNOs will increasingly investigate the potential for new or previously unexploited technologies (such as an integrated Smart Grid approach incorporating distributed generation, demand side management and energy storage management technologies) in order to either improve the utilisation of existing distribution system assets, or to provide new distribution infrastructure with reduced environmental impact and acceptable levels of technological risks.

The current passive operating philosophy of electrical distribution networks has led to the over-sizing of distribution network components during the design stage in order to accommodate any reasonably anticipated load growth. In cases where secure system operation could not be maintained with the existing distribution network capacity, traditional network reinforcement practices have typically been employed by DNOs, the costs and considerations of which are described in Chapter 4.

2.4 The Active Approach (‘Smart Grid’)

A Smart Grid operational approach uses robust two-way digital communications, advanced sensors, distributed computers and control equipment in order to intelligently integrate the behaviour and actions of all participants in the electricity system. The aim is to allow more dynamic, real-time flows of information on the system and more interaction between suppliers, network operators and customers. Smart Grids can assist in delivering electricity more efficiently and reliably and from a more complex network of generation and energy storage sources than the existing distribution system. This is because Smart Grids allow electricity retailers and distribution network operators to receive more detailed real-time information about distributed generation and demand, thereby improving the ability of the DNO to manage the system and shift load to off-peak times. In addition, customers have more information and a greater control over their electricity use, allowing them to potentially reduce costs and greenhouse gas emissions.

Smart Grids can reduce reliance on expensive peaking power plants, reduce the need for new generation capacity and reduce the additional physical distribution network capacity that will need to be created through network reinforcement and/or network expansion. Example benefits to electricity companies, customers and the society in general may include:

- Lower electricity costs to consumers (by displacing expensive peaking power plants).
- Lower transmission and distribution losses (as a result of improved grid optimisation and placing distributed generation closer to load).
- Lower operation and maintenance costs (due to reduced operation and maintenance activity and from lower equipment failure costs).
- Reduced cost of customer interruptions and customer minutes lost (as a result of fewer and shorter customer interruptions).
- Improved power quality and energy security.
- Reduced impacts due to climate change as a result of reduced greenhouse gas emissions.
- Improved asset management practices (thereby extending asset lifetimes and reducing capital equipment costs).
- Deferring the need for grid reinforcement and/or grid expansion (thereby resulting in deferred capital costs).
- Reduced meter reading costs and electricity theft.

Since the growth of PiVs and heat-pumps (but also of micro-generators, distributed energy storage units and other demand response units) is consumer-driven and not centrally planned, and takes place in an incremental and currently unpredictable fashion, it is difficult for DNOs to provide an accurate cost comparison between traditional network reinforcement and Smart Grid solutions. In order to accommodate the increased power flows associated with PiVs and heat-pumps, the capital expenditure of upgrading distribution network equipment may in some cases be less costly than applying active control techniques. However, if future electrical distribution networks are to realise their full potential in order to support the challenges associated with the transition to low-carbon electricity, other issues need to be taken into account which may not be realised by employing passive, network reinforcement practices. Hence, although network reinforcement practices were considered adequate in the past to accommodate increasing load growth, future distribution networks are likely to move away from the conventional passive control approach and towards a higher degree of network operational management.

2.5 The Intersection Between Smart Grids and Electric Vehicles

The development of a Smart Grid that interfaces with PiV chargers and is integrated with the existing smart metering infrastructure will bring together electricity companies (power generation, transmission, distribution and retailers), IT companies, technology and service providers, local authorities and car park operators with the PiV industry (car and battery manufacturers, PiV recharging station companies etc). From the DNO point of view, DNOs have traditionally had their own Local Area Networks (LAN) and Wide Area Networks (WAN) or Field Area Networks (FAN) to transfer data both to and from various points of the distribution network. However the missing link so far has been to bridge the communications gap between DNOs to the end-user, and vice versa.

As a result of wide-scale smart metering and Advanced Metering Infrastructure (AMI) deployments that replace traditional mechanical meters with advanced digital meters (or install digital sensors and meters in places where such functionality was not previously available), this missing link is now being addressed in various demonstration projects worldwide. Furthermore, the AMI concept extends to the network inside the customer's house or building (HAN), which could allow end-to-end communications from the DNO control centre all the way to specific intelligent electric appliances inside houses or buildings, such as refrigerators, dish-washers, air-conditioning units, PiV chargers etc. This allows all participants in the electricity system to make more informed decisions with regards the production and consumption of electrical power. It can therefore be said that Smart Grid technologies will be responsible for solving the scale-management problem that will arise when a vast number of new controllable devices will be added to the electrical distribution system.

One of the most important future applications of a Smart Grid will be the efficient integration of PiVs to the electrical distribution system. The coordinated recharging of PiV batteries in a wide area can allow for both the possibility of storing electrical power (ideally from renewable, intermittent sources such as wind) which might otherwise be curtailed, as well as for the possibility of exporting stored electrical power back to the home or grid during periods of maximum demand 'Vehicle-to-Home/Vehicle-to-Grid' (V2H/V2G),acting as back-up generation. V2H/V2G would bring the opportunity to go further in managing the capacity constraints with the major benefit of delaying or avoiding costly investment in infrastructure capacity upgrades. For example even if intelligent recharging is in place, there will always be some PiVs which their owners require to be charged immediately whatever the cost. If these were balanced by other PiVs discharging, then overall peak consumption will be reduced.

Most researchers expect the leading two main challenges with regards Smart Grids and PiV recharging to be:

- Co-ordinated smart recharging, i.e. the ability to smooth the recharging of large numbers of PiVs in order to avoid huge daily peaks in electrical demand.
- How to export electrical power back to the grid such that the expected life-time of the PiV battery is not significantly altered or left undercharged when the driver wishes to use the vehicle.

From the DNO point of view, coordinated smart recharging maximises the utilisation of existing distribution system assets (such as cables, transformers, switchgear etc), while it can also extend their lifetime and delay the need for network reinforcement.

The key contribution of the Smart Grid will therefore be in minimising the technical impacts caused by connecting PiVs to the electrical distribution system (as described in Chapter 3), as well as allowing them to be charged during times of low-to-minimum demand, when inexpensive base-load generators are used and large spare generation, transmission and distribution capacity is available. However, it is not reasonable to expect customers that lack real or near real-time information about electricity prices and grid congestion to alter their demand profiles according to the needs of the electricity system. Hence, software applications and systems will be required to be installed at individual customer premises (as demonstrated by the HAN and intelligent home energy management concepts) in order to provide this functionality to the customer. For example, this could allow the PiV owner to schedule PiV recharging via a web interface or a smart-phone application. In the United States, for instance, SAE International is developing a range of standards for energy transfer to and from the grid including SAE J2847/1 ‘Communication between Plug-in Vehicles and the Utility Grid’ [14].

While the precise techniques to accurately coordinate smart recharging are still being explored by various researchers, the concept of an electricity retailer or DNO managing PiV recharging schedules may cause great concern to some individuals, who may view it as disruptive to their individual needs. The solution therefore will be to allow customers to have the final say on the recharging schedule they require, with the large-scale deployment of smart meters playing a key role. Smart meters can bridge the information gap between the customer and an electricity retailer or the local DNO, however in order for this to work Time-of-Use (ToU) pricing must be implemented, and also information with regards grid congestion must be visible to the customer. Additionally, this end-to-end grid intelligence provided by the Smart Grid concept, along with the potential proliferation of small-scale distributed generation may allow for a range of recharging options to PiV owners. However, it should also be mentioned here that currently it is not clear how the electricity retail market would work if both DNO and the electricity retailer have control over PiV recharging schedules, i.e. who would have priority if for example the DNO instructs a PiV battery charging load to lower demand in order to limit currents in the secondary distribution circuit, while at the same time the price signals sent by the retailer indicate that a cheap tariff is available, thereby encouraging PiV recharging to take place. The development of dynamic Distribution Use of System (DUoS) charges to resolve this conflict is discussed in Chapter 6 on Demand Side Management.

Presently, the priority of the smart metering implementation programme, as described earlier, is to originally install smart meters with a limited functionality, with confirmation of the functional requirements and technical specifications occurring no later than winter 2011. Hence, the details with regards to developing the overall system architecture, as well as the home energy management system architecture, to allow for the real- or near real-time control of PiV recharging (or small-scale embedded generation) have not currently been explicitly stated. Hence, it is likely in the near future that demonstration projects funded by the Low Carbon Networks Fund (LCNF) and the Innovation Funding Incentive (IFI) may assist the electricity and the PiV industry to better address questions on the intersection between the Smart Grid and PiV recharging.

In summary, the main contributions of the Smart Grid concept to the efficient integration of PiVs are:

- Providing the smart meter to allow for real-time two-way metering capabilities (for SSEG or vehicle-to-grid functionality), as well as for communicating with the DCC. If dynamic pricing is considered, smart metering functionality can encompass PiV recharging tariffs and thereby provide increased economic benefits for the PiV owner.
- Avoiding excessive demand peaks through demand response techniques: this can result in electricity cost savings for the consumer, reduced generation costs and Transmission and Distribution (T&D) capital savings, as well as environmental benefits.
- Balancing demand through demand response techniques with intermittent, renewable generation: this can result in electricity cost savings for the consumer, economic benefits to companies investing in renewable energy, as well as environmental benefits.
- Realising the Vehicle-to-Grid concept to provide ancillary services to the local DNO (for example automatic generation control or voltage/frequency control): this can result in economic benefits to PiV owners, reduced generation costs and T&D capital savings, as well as environmental benefits.
- Increasing the efficiency of the overall electricity system: this can result in electricity cost savings for the consumer, reduced T&D losses, as well as environmental benefits.

3 Challenges and Constraints on the Distribution Networks of Large Uptake of PiVs

There are a number of network constraints that need to be considered with respect to the connection of PiVs to public Low Voltage (LV) distribution networks in GB. This stems from the fact that the existing technical planning and operating framework within which electrical distribution networks are managed was not envisaged with PiVs in mind. Traditionally, electrical distribution networks in GB have been designed and operated based on moderate annual load growth scenarios. However, with the anticipated growth of electrical loads such as plasma TVs, heat pumps and air-conditioning units, as well as with the potential mass-scale uptake of PiVs, GB's electrical distribution networks in the future may be required to accommodate significantly greater aggregate loads and with different daily, seasonal and geographic loading patterns to those experienced in the past.

The potential proliferation of PiVs will have an impact on the operation of electrical distribution networks both at the Low Voltage (230/400V) customer ends, as well as the Medium Voltage (1kV-50kV) and High Voltage (>50kV) levels through primary and secondary distribution transformers. If the penetration of PiVs in the overall car population in GB reaches very high levels, this may result in serious technical impacts relating to power quality, distribution system efficiency and potential equipment overloads that will be explained here. These issues will depend on both the technical characteristics of the public distribution networks that PiVs will be connected to, as well as on the timing, location and the required rate and duration of PiV battery recharging. In turn, these will depend on the usage of PiVs, as well as on the battery technologies and recharging interfaces employed.

From the DNO point of view, PiVs represent a new type of load which is different compared to some of the traditional electrical loads due to the highly mobile and unpredictable nature of PiVs. Mass-scale adoption of PiVs in the future will have an influence on the way electrical distribution networks are designed and operated. In general, there are four key factors which will have an influence on the impact of PiVs on the electrical distribution system:

- Technical characteristics of the existing distribution system itself.
- Technical characteristics of the battery charger.
- Technical characteristics of the PiV.
- The user profile.

There is a clear distinction between inherent distribution network characteristics, i.e. the technical characteristics of the distribution networks prior to any PiVs being connected, and the additional electrical load added to the distribution system due to PiV recharging.

For the first factor, it is necessary to consider the existing capacity of the distribution network in question. Distribution network capacity depends on security of supply considerations (according to Engineering Recommendation P2/6 [15]), along with thermal, voltage and fault level constraints. Hence, some of the typical parameters that need to be considered by DNOs here are network loading conditions, network topology, power factor profiles, distance from a major distribution system node, the technical characteristics of the distribution system assets used (overhead lines, underground cables, power transformers, switchgear) etc.

Regarding the technical characteristics of the battery charger, these will be closely linked to the requirements of the PiV as well as the capacity of the available electricity supply.

Two main aspects must be considered here: firstly, the electrical load required which will be different for each PiV depending on the efficiency of the battery, the type and range of vehicle and how laden the vehicle is (i.e. the state of charge of the battery). Secondly, PiV battery chargers will also have an impact on the power quality of the network, especially if there are clusters of PiVs all recharging at the same time on a weak part of the network as will later be explained. This problem could be compounded if fast-charging at public recharging stations is considered.

With regards to the technical characteristics of the PiV, the speed and range of the vehicle, and therefore its battery type and design, are likely to be the most important factors when considering the impact of PiV recharging on the electrical distribution system. Significant recent developments in battery technology, and in particular lead-acid, lithium-ion, nickel-metal hydride and nickel-zinc batteries, have raised hopes for improving overall PiV speed and range. In addition, other factors regarding the design of the vehicle which affect PiV speed and range must be considered, such as the design of the chassis and body, vehicle weight, air drag reduction etc.

Finally, the user profile will have an effect on the mileage driven by the vehicle, which in turn will have an effect on the electrical load required to cover the needs of the user. In general, typical PiV users are divided into three categories:

- Domestic vehicles.
- Fleet vehicles.
- Public transport vehicles.

In addition to the amount of electrical energy required, user profile will also have an effect on both the timing and the location of PiV battery recharging required. Timing refers to the time, day and season that PiV recharging takes place, while location refers to the phase and network location of the electrical distribution system where the user charges their PiV.

Since the current electrical distribution systems in GB have not been designed with PiVs in mind, a number of network constraints could be encountered following a wide-scale adoption of PiVs. This is because the existing networks might not be able to accommodate the increased electrical demand due to PiV recharging. For the purposes of this report, the following network constraints have been considered:

- Steady-state customer voltage drop.
- Transformer and cable thermal limits.
- Steady-state voltage unbalance.
- Increase in network losses.
- Fault level contribution.
- Other power quality issues, such as harmonics and step voltage changes.

As will later be explained, the majority of these issues arise when large numbers of PiVs require recharging at the same time as the peak domestic load. Different distribution networks will have different technical characteristics as well as different levels of PiV penetrations and thus the order in which the identified network constraints will be encountered will also differ.

3.1 Steady-state Customer Voltage Drop

DNOs in GB have an obligation to supply their LV customers at a steady-state voltage within the specified limits of 230/400V +10/-6% [16]. Under these regulations, the voltage is not permitted to exceed these limits, although it may transiently do so under exceptional conditions in the network such as, for example, during fault conditions. Maintaining steady-state customer voltages is therefore managed differently to maintaining customer supply, with the former having specific statutory limits that the DNO has to plan for, while the latter is generally being driven by the CML (Customer Minutes Lost) and CI (Customer Interruption) network operational incentive schemes provided by Ofgem.

In order to minimise associated costs with system equipment, LV distribution networks have traditionally been designed to use the majority, if not all, of this allowable voltage deviation. Voltage profiles in the network are assessed at the planning stage and transformer tap changers (usually with line-drop compensation) are employed in order to accommodate variation in system demand. In addition to load-tap-changing transformers, supplementary line regulators and switched capacitors on feeders are also often used for voltage regulation purposes.

Hence, DNOs have traditionally set steady-state voltages at source substations near the top statutory limit during minimum loading conditions in order to allow for downstream voltage drops where customer voltages may approach the bottom statutory limit (230/400V -6%) during maximum loading conditions. PiV recharging, however, will lead to an increase of the aggregate loading conditions in the distribution system, which could potentially result in customer voltages dropping below their lower limits at some vulnerable points of the network. For effectively all LV distribution networks in GB, the impact of recharging any individual PiV will be almost negligible on the overall distribution system. However, when the aggregate capacity of these vehicles reaches a critical threshold, steady-state voltage studies must be undertaken by the local DNO in order to ensure that all customer voltages are maintained within their statutory limits. Furthermore, clustering of PiVs at a particular network and phase location of the distribution network could allow significantly lower PiV penetrations to be accommodated compared to a uniform PiV deployment. Thus it is important to take into account both the network as well as the phase location of the connected PiVs when considering the penetration of PiVs that may be accommodated before under-voltage statutory limits are exceeded.

Because there is currently very little monitoring and control carried out at the LV levels of electrical distribution networks, the DNO will rarely be aware of an under-voltage being encountered at a customer’s terminals. Whilst the domestic customer may also not observe this under-voltage, the customer’s electrical equipment is designed to operate within those statutory limits and operation outside of these limits may damage the equipment. DNOs will usually be aware that there is an under voltage problem after receiving a customer complaint and they have a maximum response period of six months to investigate the cause of under-voltage as well as to bring the customer voltage back within the acceptable statutory limits. However, because the existing performance measures (as specified by the Guaranteed Standards) are based on DNO response time to complaints rather than the actual number of complaints received, DNOs have currently little incentive to provide improved voltage control for domestic LV customers. Hence, it can be argued that the current approach for voltage control at the LV levels is reactive, rather than proactive. The exception to this approach are some commercial or industrial customers which often have greater than average power quality needs and would therefore need to be dealt with separately by the DNO.

3.2 Cable and Transformer Thermal Limits

Transformers and network lines, such as overhead lines and underground cables, have a thermal rating determined by the maximum current carrying capacity of that component. If a component is loaded above its thermal rating for an extended period of time, it will overheat which could then lead to its permanent damage, or even to a dangerous event such as a fire or explosion. Given the very sparse nature of loading information currently available at secondary distribution substations and LV distribution networks, there might be a significant risk of undetected equipment thermal overloads if PiVs proliferate as anticipated.

The different types of thermal ratings that can be quoted by DNOs are:

- Continuous ratings, which indicate 100% rated current for 100% of the time.
- Cyclic ratings, which are based on a specific load-shape, load-duration etc.
- Seasonal ratings, which are based on a seasonal variation.

In order to minimise network reinforcement costs, DNOs often operate their assets close to their thermal limits during maximum loading conditions (a concept known as ‘asset optimisation’). Assuming that the local electrical demand exceeds the distributed generation embedded in that network section (as for nearly all LV network feeders in the UK distribution system currently), PiV recharging will lead to an increase in the electric currents flowing in the network, thus bringing system components closer to their thermal limits. PiV recharging is likely to increase both the base loading, for example during off-peak recharging in the night, as well as the peak loading, for example during 5.30-7pm when customers are returning to their premises. If this only occurs for relatively short periods and by a small margin, upgrading these assets may not be required by the local DNO. However, because PiV recharging is likely to occur over relatively long periods and at similar times, this statement is unlikely to apply. This could have serious implications to the life-time of the DNOs assets, which might be significantly reduced, or may need to be replaced and/or upgraded sooner than previously planned by Asset Management. The most vulnerable distribution networks will be the ones that are already operating close to their thermal capacity, such as ‘tapered networks’, i.e. distribution networks that have been designed in order to match capacity to the lower level of loading observed further from the source of supply.

Since the majority of LV distribution networks in GB have a radial topology, the line sections that will be affected the most by the increase in power flows due to PiV recharging are those where the PiVs will be connected. For some cases where the distribution of PiVs is not equal with regards their phase connection, it is possible that the thermal limits of the neutral conductors of the lines supplying the network may be exceeded even before the respective phase conductors. This is because cables with neutral conductors of smaller cross-sectional areas are often employed to minimize costs. For the majority of LV distribution networks, however, violation of the thermal limits of the phase conductors is anticipated to present a more limiting network constraint.

With regards to distribution transformers, these are typically referred to in terms of operating voltage (in kV) and nominal apparent power rating (also known as kVA rating). Their kVA rating indicates the amount of apparent power that can be transferred between their two sets of terminals. Load flow studies must be undertaken by the local

DNO to ensure that distribution transformer thermal limits are not exceeded due to PiV recharging. It should be noted, however, that it is not uncommon practice for DNOs to operate their transformers above their ratings for relatively short periods and small margins. It is therefore necessary to investigate both the extent as well as the time duration that distribution transformer overloads may occur in order to determine whether asset replacement is required due to the introduction of PiVs to the distribution system.

3.3 Steady-state Voltage Unbalance

Voltage unbalance in three-phase distribution systems is a condition in which the three-phase voltages differ in amplitude or are displaced from their normal 120° phase relationship or both. Voltage unbalance is usually defined as the maximum deviation from the average of the three-phase voltages, divided by the average of the three-phase voltages and expressed as a percentage. A common definition is also given by using symmetrical components and is used in Engineering Recommendation P29 [17] which defines the acceptable levels of voltage unbalance GB LV networks. The percentage Voltage Unbalance Factor (% VUF) is determined by the ratio of the negative to the positive sequence voltage component and has a design limit of 1.3% in the UK, although short-term deviations (less than 1 minute) are allowed up to 2%. Similarly with excessive customer voltage drops, currently DNOs are rarely aware of unacceptable voltage unbalance being present in their distribution networks since there is very little monitoring and control carried out at the LV level. Their response to voltage unbalance is thereby reactive and driven by individual customer complaints

The main reasons for voltage unbalance is that single-phase loads in LV distribution networks are continually connected to, and disconnected from, the distribution system and are not evenly distributed between the three phases. Additionally, the level of unbalance present in distribution networks also depends on phase-conductor configurations, such as unsymmetrical spacing between phase conductors. Voltage unbalance until now has generally not been of great concern for DNOs because the distribution of single-phase customer loads has been centrally planned by allocating them as equally as possible across the three phases.

Since the overall electrical load in the distribution system will be increased with the introduction of PiVs, the concern for DNOs is that the degree of unbalance may also increase. The majority of PiVs are anticipated to charge using single-phase connections from either household sockets or public recharging points. Three-phase connections may also be used, however it is likely that single-phase connections will dominate due to their ease of deployment. The single-phase nature of PiVs, along with the fact that their growth will be consumer-driven and not centrally planned by DNOs may result in additional unbalanced currents and voltages GB distribution networks. However, if, as anticipated, the distribution of PiVs is random with regards the split between the three phases, the overall unbalance caused by the introduction of PiVs to the distribution network should remain similar to existing levels. In addition, load behaviour is also likely to change significantly in the future as previously explained, adding further complexity to the inherent symmetry of distribution systems. Excessive unbalanced voltages can result in adverse effects on power system equipment and on the electrical distribution network, which is intensified by the fact that a small unbalance in the phase voltages can cause a disproportionately larger unbalance in the phase currents. Hence, voltage unbalance studies may need to be undertaken by the local DNO to ensure that the proliferation of PiVs does not cause voltage unbalance statutory limits to be exceeded.

With regards to fast recharging from public recharging points, the significantly higher rates of recharging may cause voltage unbalance problems for DNOs if single-phase fast-charging points are employed. However, it is anticipated that three-phase connections will dominate, and also fast-charging points will be centrally planned by DNOs in order to ensure overall balance with regards their phase connection. Hence, it is unlikely that fast-charging will have an impact on the connected customers.

3.4 Increase in Network Losses

A proportion of the electrical power that is transferred from the generation stations to the point of utilisation is dissipated as heat in the form of network resistive losses. The increase in electrical power flows in a distribution system due to PiV recharging will also have an effect on system losses. Since losses are a quadratic function of the electric current in the network, the greatest losses occur during maximum loading conditions in the network. In order to determine the impact of PiV recharging on system losses it is necessary to consider both worst-case, deterministic scenarios (i.e. the periods throughout the day when system losses are increased the most), as well as the overall contribution of PiVs throughout the day using stochastic modelling.

For underground cables and overhead lines, the majority of losses are conductor losses due to their impedances. The dielectric losses and sheath losses at voltage levels of distribution networks are relatively small compared with conductor losses and may be neglected. In addition to network lines, distribution transformers are also responsible for technical losses. Transformers have fixed losses that are the heat losses within the iron core (hysteresis and eddy current losses) and load losses represented by the heat produced by the current flowing through their windings (resistive copper losses). These may be calculated using the short-circuit resistance of the transformer and the output current.

The increased power flows transferred through the distribution system due to PiV recharging are anticipated to result in higher network losses. Hence, load flow studies must be performed by DNOs in order to quantify the impact of PiVs on network losses, in particular under high PiV penetration scenarios. However, it can be argued that these losses originate from a higher utilisation of existing assets in the system, and they should therefore not be considered as an indication of inefficiency. Hence, the most significant impact to DNOs with regards network losses due to PiV recharging is anticipated to be regulatory (rather than technical), since DNOs have strict targets from Ofgem in order to reduce the load losses incurred on their distribution networks.

Similarly to transformer and cable thermal limits, the most vulnerable distribution networks with regards to network losses will be the ones whose loading patterns will be affected the most by the introduction of PiVs. For such networks, system losses during peak loading conditions may be significantly increased unless Demand Side Management (DSM) techniques are employed for managing PiV recharging demand (a concept known as ‘peak shaving’ or ‘load shifting’). This would then also have a positive effect on system losses due to the reduced power flows in the system, thereby resulting in reduced load losses.

On the other hand, if ‘V2G’ functionality is considered, whereby PiV battery recharging devices operate as embedded generators, PiVs may have a positive effect by providing network loss reduction as an ancillary service to the local DNO. However, it is likely that the electrical power from the vehicle would need to be consumed locally and not exported back to the electrical grid due to the significant difference that exists in the wholesale and retail price of electrical energy. Hence, considerable tariff incentives would need to be in place in order for such functionality to make commercial sense to the customer [18].

3.5 Fault Level Contribution

At any given moment, every point in a distribution network has a particular fault level, which is a measure of the current that would occur in the event of a solid three-phase/single-phase short circuit at that point. Fault levels are expressed in units of apparent power, typically in terms of either kVA or MVA. The fault levels in a distribution network can change over time, due to changes in the configuration of the network. Thus, a single value for the fault level at any network point is not truly indicative. Instead, minimum and maximum values are usually specified for the fault level at a particular network point and the actual fault level varies within these values.

With the introduction of PiVs to a LV distribution network, the fault levels on that network close to the point of PiV connection could be increased. Battery chargers do not inject fault current into the network as there is no path for the DC battery to feed into the network. However, fault in-feed might be a possibility where PiV battery recharging devices may operate as embedded generators, taking electrical power from the vehicle battery and feeding it back into the distribution network when it would be needed (‘V2G’ functionality). In reality, however, the most likely contribution of PiVs to increased network fault levels would be due to changes in the configuration of the network in order to accommodate the increased aggregate load due to PiV recharging. This is because distribution substations may be fed by more transformers (in parallel) to meet the additional load, therefore increasing fault levels.

The fault contribution of the PiV will depend on the distance from the fault and also on the PiV operation during fault conditions. In turn, this response will depend on the control algorithm of the inverter. If the PiV is able to quickly switch off in the event of a fault, its fault level contribution is generally very low and should not present a problem for the local DNO. However, if the PiV remains connected during the fault, increased fault currents must be taken into account for protection measures. For densely populated urban and sub-urban distribution networks, in particular, where the existing fault level may already approach the rating of the switchgear, increase in network fault levels could present a serious challenge due to the very high associated costs of up-rating distribution network switchgear. However, LV distribution networks mostly use fuse protection which have high margins for fault level capability, while for MV distribution networks the fault contributions are likely to be within existing standards (Engineering Recommendation G74 [19]) due to the short-circuit currents produced by the majority of inverters being usually very low. Hence, the integration of PiVs is not anticipated to cause considerable modifications to existing protection schemes with regards their fault level contribution.

3.6 Other Power Quality Issues

In addition to steady-state customer voltage issues and unacceptable levels of voltage unbalance, other power quality issues have been reported in the literature [20] with regards to the connection of PiVs to public LV distribution systems. These mainly stem from the fact that PiV interface devices will use power electronic converters, which are highly non-linear due to their operating principles and the presence of switching power semiconductor elements. Hence, extensive power quality studies must be undertaken by DNOs as well as PiV battery manufacturers in order to ensure that mass-scale PiV recharging does not degrade the quality of power supplied. The following two power quality issues are highlighted:

- Harmonics.
- Step voltage changes.

3.6.1 Harmonics

Harmonics are integer multiples of the fundamental frequency and, when present on an electrical distribution network, distort the pure sine-wave of the fundamental waveform. Harmonics are caused by non-linear loads, which are devices that contain semi-conductors such as diodes and thyristors. These loads draw harmonic currents which cause harmonics voltages to be present on the distribution system. Since the majority of electronic equipment contains semi conductors, a degree of harmonic distortion is typically present on the electricity network.

With the presence of inductive and capacitive components in the distribution system, harmonic voltages and currents may be amplified during resonance conditions. The most common effects of harmonics include additional losses in power system components (such as network lines, distribution transformers and motors), malfunction of sensitive electronic equipment, and vibrations and noise in motors. For electric cables, in particular, excessive neutral currents would flow due to triple-n harmonics and a doubling of the cross sectional area of the neutral conductors would be required in order to avoid excessive heating. PiV battery chargers and inverters may inject harmonic currents into the network and the magnitude and order will depend on inverter technology and mode of operation, however most new inverters are capable of generating a very near sine wave.

During PiV recharging, the current demand varies based on the State of Charge (SoC) of the battery and depending on the charger configuration the Total Harmonic Distortion (THD) of the input current can vary from less than 5% to more than 50% [21]. Due to the unique technical characteristics of each type of PiV battery charger, no two charger models produce harmonic distortion in an identical fashion. The overall effect of adding groups of PiV battery chargers on a network line does increase the harmonic current, but the THD decreases when charger loads are linked because harmonic phase cancellation takes place. Harmonic limits for UK distribution networks are specified in Engineering Recommendation G5/4 [22].

Power quality studies must therefore by undertaken by DNOs to ensure that the power delivered to customers is within acceptable harmonics limits for distribution networks with high PiV uptake. The most vulnerable distribution networks will be those with high harmonic levels even prior to any PiVs being connected in the network (for example due to rail infrastructure), as well as distribution networks where clusters of PiVs are connected at weak parts of the network and where PiV penetration is significant. In general, it is likely that lightly loaded electrical distribution networks will be more vulnerable because they have less load-damping effect compared to heavily loaded electrical distribution networks.

3.6.2 Step Voltage Changes

As previously mentioned, it is anticipated that the impact of recharging any individual PiV will be almost negligible on the feeder primary. However, the process of connecting or disconnecting a cluster of PiVs at the same time may cause step voltage changes at their connection point on the network. The magnitude of a step voltage change depends mainly on the method of charger control (i.e. on the charger/inverter characteristics), as well as on the types of load connected, the presence of local embedded generation and the strength of the distribution network. Their acceptable level and frequency of occurrence are specified in Engineering Recommendation P28 [23] and therefore power quality studies must be undertaken by DNOs as well as PiV battery manufacturers in order to ensure that PiV recharging does not degrade power quality in an electrical distribution network with high PiV penetration. However, it has previously been reported [24] that step voltage changes are not likely to present significant concern for DNOs due to the relatively low rate of recharging and due to the operation of the inverter present in the PiV recharging interface. This can be achieved by controlling inverters to limit initial recharging currents and hence the change in power output levels. In addition, in order to counteract voltage sags, inverters may be controlled to supply reactive power for voltage support during a sag. In general, the most vulnerable networks with regards unacceptable step voltage changes will be LV distribution networks where clusters of PiVs are connected at weak parts of the network and where PiV penetration is significant. As far as home recharging is concerned, the majority of PiVs are anticipated to charge using standard 13A sockets and therefore the impact to the network will be almost negligible. For faster recharging, however, strict regulations must be in place to ensure that the level and frequency of occurrence of step voltage changes are not outside the current statutory limits.

3.7 Ranking of Network Constraints

As previously mentioned, there are four key factors which will influence the impact of PiVs on the electrical distribution system:
- Technical characteristics of the existing distribution system itself.
- Technical characteristics of the battery charger.
- Technical characteristics of the PiV.
- The user profile.

These factors will also determine which network constraints will be the most limiting for PiV deployment and will require mitigation by the local DNO.

Different distribution networks will have different technical characteristics as well as different levels of PiV penetrations and thus the order in which the identified network constraints will be encountered will also differ. An important concept to consider here is the concept of ‘load diversity’, which guarantees that the sum of the instantaneous peak demand of a group of customers in a network is always less than their maximum total electrical demand. Load diversity may be expressed mathematically as the ‘coincidence factor’ which is equal to the ratio of the maximum coincident total electrical power demand for a group of customers to the sum of the peak electrical power demand of each customer in that group. As the number of customers on the LV distribution network increases, the coincidence factor reduces significantly at first but less significantly for high number of customers. Similarly, while an average residential customer may have a typical load factor (i.e. the ratio of average load to peak load) of between 0.15 – 0.25, as the demands of more customers are aggregated this value increases significantly at the distribution and primary substation levels.

For sparsely populated rural distribution networks, where the coincidence factor is typically high, the impacts of PiV recharging might be more pronounced, especially if synchronous peak loading patterns are observed. This is because the additional electrical demand due to PiV recharging will affect the total demand in the network more significantly compared to networks with high numbers of customers and where load diversity is high. Due to the low number of customers connected, however, rural distribution networks are less often operated close to their thermal capacity and therefore transformer and/or line overloads are not anticipated to present as limiting a constraint as for urban and sub-urban distribution networks. On the contrary, however, customer voltage drops are more likely to be encountered due to the long, high-impedance network lines present in rural areas. Under a worst-case scenario, voltage unbalance and other power quality problems may arise, especially for networks whose existing power quality levels are already poor prior to connecting any PiVs.

Research [25] has shown that PiV uptake is anticipated to be higher in urban and sub-urban areas compared to rural areas, because customer driving and recharging requirements are more likely to be satisfied there. For such networks, thermal constraints are anticipated to be the most limiting constraint to the integration of PiVs, and hence network reinforcements may be necessary in the most adversely affected areas. Even if thermal limits are not exceeded in the distribution system with the existing loads, the additional load due to PiV recharging can accelerate the time frame when primary and distribution transformers will need to be upgraded and thus alter the pattern of expansion for the local DNO. In addition to thermal constraints, excessive customer voltage drops may also be observed in such networks if PiV recharging is not coordinated, either through financial incentives for off-peak recharging or through direct utility control. Finally, power quality problems and in particular harmonics due to the non-linear nature of PiV batteries and their interface devices may also arise because of the anticipated high number of customers with an PiV, especially for networks whose existing power quality levels are already poor prior to connecting any PiVs.

Regarding the fault level contribution of PiVs, these may be more of an issue in dense, urban networks where fault levels may increase due to potential changes in the configuration of the distribution system to accommodate the increased aggregate load due to PiV recharging. Similarly, the greatest increases in network load losses due to PiV recharging will also be observed in dense, urban or sub-urban networks because load losses are a quadratic function of the current and the highest current flows occur in such networks. However, it is unlikely that either constraint will present significant cause for concern for DNOs or that significant network reinforcement will be required to mitigate them.

Table 3-2 summarises the findings of this report and provides rankings for the likelihood of encountering each of the six identified network constraints for urban, sub-urban and rural distribution networks.

Network Constraint	Network Type		
	Urban Networks	Sub-urban Networks	Rural Networks
Customer Voltage Drop	3	2	1
Transformer and Cable Thermal Limits	1	1	2
Voltage Unbalance	6	6	4
Increase in Network Losses	4	4	5
Fault Level Contribution	5	5	6
Other Power Quality Issues	2	3	3

Table 3-2: Ranking of Likelihood of The Identified Network Constraints due to Piv Recharging

As previously mentioned however, different distribution networks will have different technical characteristics as well as different levels of PiV penetrations and thus the order in which these network constraints will be encountered will differ. In general, while some diversity in PiV recharging will be realised practically in all electrical distribution networks, the uncertainty with regards potential PiV uptakes, as well as recharging and driving patterns make it inherently difficult to accurately quantify the impacts of PiVs on the distribution system and also determine which network constraints will be the most limiting for PiV deployment. Due to socio-economical reasons [26], PiVs are likely to be clustered in certain parts of the distribution system, thus exaggerating their potential negative technical impacts to the distribution network. DNOs will therefore be required to undertake primary and secondary level distribution system analyses in order to determine the PiV penetration levels and battery recharging behaviours that may result in adverse impacts that require mitigation. PiV impact analyses must accurately take into account both the location, as well as the timing and duration of PiV recharging required, and therefore a degree of spatial and temporal diversity will be needed to provide a deterministic as well as stochastic consideration of the potential PiV impacts to the electrical distribution system.

In addition to clustering, the wide-scale adoption of high-power, fast-charging points could further increase the negative impacts of PiVs to the distribution network if not carefully planned. Although this is a concern, the provision of these points would be centrally planned by the relevant DNO. High-power fast-charging points of around 50-60kW are typically being considered for GB, and up to 150kW elsewhere, which would require three-phase connections and direct connections to the secondary distribution transformer using dedicated infrastructure. This would mitigate against many of the technical issues associated with high-power fast-charging points described in this report, however it is likely that there might be a requirement for reviewing the connection process for these types of connections, with more referral to the DNOs Asset Management department likely to be required than for a typical domestic supply.

The majority of distribution network constraints considered in this report arise when large numbers of PiVs require recharging at the same time as the peak domestic load. It should also be noted, however, that currently there are a number of new initiatives and technologies that are related to a more efficient use of the electrical distribution system, such as:

- Smart chargers that can manage PiV recharging times and rates.
- Demand response technologies for load shifting purposes.
- Micro-generation technologies (such as small-scale photovoltaics, wind-turbines or combined heat and power units) installed at homes and businesses, particularly so after the new feed-in tariffs mechanism implemented by the UK Government for small-scale embedded generation [26].
- Electricity tariffs that encourage use in non-peak periods.
- Load reductions realised through energy efficiency programs and smart-metering.

These initiatives could mitigate the overall increase in system loading due to PiV recharging and thus alleviate the need for significant network reinforcement. However, most of these are in their early stages of development and therefore DNOs must closely monitor major progresses made in order to attempt to quantify the potential benefits and associated costs from their prospective implementation.

4 Description and Cost of Reinforcement/Mitigation Options

DNOs compile a variety of critical information on all assets installed on their distribution system, such as distribution circuits and their ratings, switchgear and transformer assets. This information, together with actual and forecast demand data, is used to assess the utilisation of network assets to determine the need for network reinforcement, its timing and scale. This is typically achieved by considering the existing demand on a substation, the underlying growth rate projections and any future demand increases due to specific known developments, in order to allow estimates to be made as to when the substation capacity will be insufficient to support the predicted demand. Also, the transfer capacity available under first and second circuit outage conditions must be considered, as specified in Engineering Recommendation P2/6 [15]. The Asset Management function of the DNO is typically responsible for developing strategies to achieve optimal timing of network reinforcement.

When identifying a shortfall in distribution network capacity, the traditional solutions by DNOs to enhance system capacity have focused on distribution network reinforcement practices (such as re-conductoring circuits or the introduction of additional overhead lines and underground cables), or upgrading to a higher operational voltage in order to increase the electrical power that can be accommodated. However, it is recognised that some of these methods, and in particular those involving the construction of new overhead line sections, can be difficult to achieve due to planning constraints, as well as environmental issues that can result in long delays and/or significant additional capital expenditure.

As a result, it is likely that DNOs in the near future will increasingly investigate the potential for new or previously unexploited technologies, such as an integrated Smart-Grid approach incorporating distributed generation, demand side management and energy storage management technologies in order to either improve the utilisation of existing distribution system assets, or to provide new distribution infrastructure with reduced environmental impact and acceptable levels of technological risk. However, when considering the potential use of these technologies on the UK electrical distribution system it is important to ensure that all issues associated with these systems (technical, commercial and environmental) are fully understood prior to installing and testing them on the distribution network.

It should also be noted that DNOs are becoming increasingly concerned with the gradually increasing load factors present as well as the significant growth in summer loads that has recently been observed, particularly in the South. This is because both of these parameters can have significant implications for the ratings of the distribution system assets that they are operating. As far as PiV integration is concerned, this means that in some cases the particular cyclic characteristics of a new load could be such that the daily or seasonal peak demand will fall within an existing demand trough, while it could also add directly to the existing demand peak. While the former case may appear at first to be beneficial, it may still cause concern to DNOs since it will increase the load factor, possibly to the extent that the cyclic rating of the existing distribution system assets is exceeded. In addition, this increase could in some cases reduce transformer maintenance windows, thereby also having serious implications for the timing of load-related network reinforcement. Hence, the general uncertainty as to the cyclic nature of the new load that will be added to the system due to PiV recharging compared to the cyclic loading on existing upstream assets is likely to cause concern to DNOs. In general, however, while flattening load peaks might be beneficial for distribution networks where assets with emergency continuous ratings are employed, this would be problematic for distribution networks where assets with cyclic ratings are employed as the DNO will no longer be able to count on the allowable overload margins during maximum loading conditions.

4.1 Potential Reinforcement/Mitigation Options

Within this section a set of potential reinforcement/mitigation options is identified taking into account possible future electricity demand and generation developments aimed in satisfying the distribution network constraints described in the previous Chapter 3. The aim of the majority of mitigation measures described here is to enhance the utilisation of existing distribution network assets in order to reduce the required distribution network reinforcement. As a result, potential reinforcement/mitigation options may include traditional network reinforcement strategies, along with a range of existing and novel distribution network control technologies and customer side measures.

Network reinforcement is a term commonly used to describe the increase in capacity or extension of the existing distribution system assets that are operated by a DNO. Due to the way that electrical distribution systems are planned and operated, at any one time there are always parts of the distribution network where the local system is either under or over-utilised. This is partly because supply cannot always be accurately matched to demand, and partly because the load required within the various parts of the distribution system is subject to change over time. For parts of the network where this unbalance is high and has reached unacceptable levels, the DNO is responsible for either operating the distribution system such that excess capacity from the area is transferred to a different area where it is needed (by transferring blocks of load between adjacent networks), or for reinforcing the existing capacity. For high voltage distribution network reinforcement, the resultant improvement in security may enable lower voltage network reinforcement to be postponed or even avoided.

Network reinforcement represents a significant capital investment for the majority of DNOs in GB and as such it is subject to strict regulations set by Ofgem. These costs include not just the capital expenditure of providing the assets that are to be installed in the distribution system, but also the operational costs of repairing and maintaining those assets over their life-time. These costs are then recovered by the DNO in accordance with their two principal sources of income:

- Through ongoing charges for the use of the distribution system by all customers connected in the system (Distribution Use of System charges – DUoS).
- Through connection charges for requests for new supplies or augmented supplies beyond the existing maximum power requirement.

The two main network reinforcement strategies employed by DNOs are:

- Reinforcement of heavily loaded assets (switchgear, transformers, overhead lines or underground cables) while maintaining the number of substations constant.
- Introduction of additional circuits and/or substations.

The strengths and weaknesses of each strategy is briefly summarised in Table 4-3.

Option	Strengths	Weaknesses
Network Reinforcement	Well understood and robust measure	Usually highest cost option
Inserting New Distribution Substations	Likely to be beneficial for new networks where more substations than minimum required can bring benefits	Limited scope for existing networks due to land and space availability. May require extension of HV network sections

Table 4-3: Traditional Network Reinforcement Strategies [30]

4.1.1 'Network-side' Mitigation Measures

In terms of existing and novel distribution network control technologies, the following have been considered for the purposes of this report:

- Voltage Control: This can be achieved by applying voltage regulators in LV and HV feeders and, as described later in this report, can be very beneficial as a significant number of network constraint violations are due to voltage.
- Phase Load Balancing: This is aimed at balancing network loading across the three phases by suitably reconnecting consumers to different phases. This would be particularly beneficial in cases of significant load imbalance between phases.
- Dynamic feeder reconfiguration: This is a technique of continuously monitoring circuit power flows and voltage profiles and switching load from one feeder to another. This option is well applicable for HV distribution networks with normally open points. It is envisaged that this technique would require presence of distribution network intelligence and remote control to provide active control of load flows and in order to manage local network constraints.
- Dynamic thermal rating: This is a technique of continuously monitoring and adjusting circuits' ratings. For the majority of LV and HV distribution networks, however, this technique would have limited applicability and is best suited for rural areas dominated by overhead lines.

The various strengths and weaknesses of these network mitigation approaches are summarised in the table below [30].

Option	Strengths	Weaknesses
Voltage Control	Potentially significant benefits, particularly in semi-rural and sub-urban LV networks	Control infrastructure not available. State estimation and real time active network management in distribution networks not yet well established. Experience with distributed voltage control in the UK limited Limited applicability in urban areas where PiV uptake may be most significant.
Phase Load Balancing	Reduces the impact of voltage constraints which may be a major driver for LV networks reinforcement in semi-rural and sub-urban networks	The extent of imbalance across different network types is unknown and therefore is difficult to assess the actual materiality and relevance of this option.
Dynamic Feeder Reconfiguration	Simple, low costs	Already in practice for loss minimisation, benefits may be limited. Cost of HV reinforcement significantly lower than LV reinforcement. Only applicable for small PiV penetration where recharging is very non-uniformly distributed More frequent switching could reduce the life of switchgear assets.
Dynamic Thermal Rating	Allows greater utilisation rates, reducing the impact of thermal constraints.	State estimation and real time active network management in distribution networks not yet well established. Experience with dynamic thermal rating control in the UK limited. Limited applicability in the majority of LV and HV networks, in particular for urban areas where PiV uptake may be most significant.

Table 4-4: Network Control Strategies [30]

Further detail around the impact on expected network reinforcement costs of voltage control as a mitigation measure is described in Chapter 8 as part of the analysis of a range of different PiV scenarios.

4.1.2 ‘Consumer-side’ Mitigation Measures

The following demand side management and micro-generation measures at the customer premises have also been considered:

- Smart PiV recharging control: Smart recharging can reduce peak loads and thereby provide an opportunity for mitigating network reinforcement due to high PiV uptake scenarios. Two recharging control options have been considered:
  - Optimised recharging to national demand.
  - Fully optimised recharging to local and national electricity demand profile.
- Smart appliances control: appliances such as refrigerators, pool pumps, air conditioning units etc. can be controlled through time shifting in order to reduce network peak demand.
- Energy efficiency: Reducing energy needs in the residential, commercial and industrial sectors from new energy efficiency measures such as micro generation, better insulation, solar heating, use of more efficient appliances and lighting, etc. can change the energy demand pattern and reduce peak demand releasing some network capacity.
- Smart heat pumps with heat storage will increase loading on the network (if the heat sector is incorporated into electric system). Coordinating heat pump operation alongside recharging of PiV may reduce requirements for network reinforcement.
- Micro Combined Heat and Power (micro-CHP): The widespread adoption of micro-CHP or other Distributed Generation (DG) could provide additional localised generation capacity which would provide headroom on the network. Although driven by heating demand, micro-CHP output could coincide with times of peak PiV recharging.
- Smart control of Domestic Economy-7 (DE7) heating load provides an additional source of potential demand that can be optimised.

The table below summarises the strengths and weaknesses of these demand-side measures. Further information on these measures and the potential benefits for differing network types can be found in [32] and [30].

Option	Strengths	Weaknesses
Smart PiV Recharging Control	Potentially very significant benefits. Improves network utilisation.	Information about intended use of PiV needed; Communication/intelligence infrastructure required; Robustness to be established.
Smart Appliances Control	Can mitigate peak increase especially when peaks are very prominent.	Value and benefits of this option likely to reduce with increase in application of smart recharging and other DSM measures that may flatten the load profile.
Energy Efficiency	Reduction in electricity demand is welcomed and will allow higher penetration of PiVs for the same reinforcement cost.	Benefits may be limited, energy efficiency may not significantly reduce peak demand.
Heat Pump Storage Control	Potentially significant reduction of peak demand increase with moderate storage capacity.	Costs associated with heat storage facility may be significant.
Micro CHP Control	Potentially significant benefits.	Non controllable as electrical output is driven by heating requirements.

Option	Strengths	Weaknesses
Micro CHP Control With Heat Storage	Potential benefits.	Benefits will be already achieved by smart voltage and PiV recharging control; Communication/intelligence infrastructure required; Robustness to be established.
Smart DE7 Heatload Control	Might provide the additional benefit if smart PiV recharging control is implemented.	No recorded benefit; If heating is done by heat pumps this option will not exists anymore; Communication/intelligence infrastructure required; Robustness to be established.

Table 4-5: Demand Side Management and Micro-Generation Strategies at Customer Premises [32]

Further detail around the impact on expected network reinforcement costs of smart PiV recharging control and heat-pump control is described in Chapter 8 as part of the analysis of a range of different PiV scenarios.

4.2 Reinforcement and Mitigation Option Costs

Network reinforcement projects may include a wide range of physical components that are to be added to the distribution network or to replace components that are already in situ. The selection for these components (and hence the ensuing grid upgrade costs) will depend on the two possible approaches for the operation and control of electrical distribution networks:

- Following the present network operation paradigm whereby the distribution network is designed during the planning stage to be able to accommodate any reasonably anticipated load growth.
- Following a shift in the network operation paradigm to a Smart Grid approach, whereby increased real-time management and control capabilities may be realised through the use of robust two-way digital communications, advanced sensors and distributed computers and control equipment.

4.2.1 Cost Considerations of The Traditional Network Reinforcement Approach

The approach following the present network operation paradigm will mainly include the following asset capital expenditure costs:

- Transformer upgrades, by adding new grid, primary or secondary transformers to the distribution system or replacing existing transformers with improved ones. These costs will also include costs incurred for connecting the transformer to the system, as well as for earthing.
- Re-conductoring of existing overloaded feeder sections, or new distribution lines on existing or new corridors (underground or overhead).
- Associated HV and LV relays and switchgear costs, such as Ring Main Units (RMUs), Air Circuit Breakers (ACBs), Air Break Switch Disconnectors (ABSDs), Reverse Power Relays (RPRs), Fault Passage Indicators (FPIs), LV cabinets/boards and pillars etc.
- Any special metering, telemetry or data processing costs where necessary.

In addition to capital expenditure related to asset costs, two further cost categories must also be taken into account with regards network reinforcement:

- Costs related to physical work, such as cable laying, jointing, fitting etc.
- Costs related to fee work, such as commercial negotiations, planning, design, operations, record-keeping, inspection, monitoring, testing and adoption of assets.

Physical work can be divided into non-contestable work which must be carried out by the local DNO and contestable work which may be undertaken by an approved contractor on the DNOs behalf. In general, a new extension to the distribution network from one or more points of coupling represents contestable work, while work upstream of the point of coupling reinforcing or re-arranging the existing distribution system represents non-contestable work and remains the responsibility of the DNO. The final connection of the extension to the existing network, its commissioning, inspection, testing and energisation is also non-contestable work, along with the planning, design and specification of both contestable and non-contestable work ('fee work').

It should also be noted here that for most DNOs in GB, the workload required in order to keep the operational performance of their distribution networks at acceptable levels is constantly increasing due to some under-spending in asset replacement, asset maintenance and/or network reinforcement in previous years and more assets reaching their replacement age. In order to try and increase distribution network capacity at the same time is likely to introduce serious logistical issues to DNOs, such as the availability of trained staff for carrying out the work required for example. Hence, DNO capital costs with regards to physical work are anticipated to increase in the future with the expected increase in electrical demand.

Finally, the costs of providing network lines or plant to meet any abnormal features or special supply requirements must also be taken into account and included in the total network reinforcement costs. It is outside the scope of this report to describe every circumstance in which an abnormal cost might arise since these circumstances are too numerous. However the most common situations giving rise to abnormal costs are the following:

- Transformer/substation/switchroom sites not provided to the DNO in optimal locations (typically due to space restrictions caused by no adjacent available land) taking account of cable access as well as access by engineering personnel. For example, this includes the laying of lengths of cable down to a basement located substation.
- Transformer/substation/switchroom sites not provided to the DNO at nominal prices or rents. For example, short-term leases/licenses or such leases/licenses provided at higher than a nominal 'peppercorn' rent.
- Connections at a higher than normal level of security of supply.
- Costs arising from special site conditions or delays which are outside the DNO's liability, for example weekend work at the request of the customer, city council or the police.
- Service termination where the customer fails to provide and/or install ducts to facilitate the installation of services into the premises.
- Multiple occupancy premises where the developer fails to provide all necessary civil work including ducts, access ways, chase and covers etc.

In addition to these, there are other less common situations that may give rise to abnormal grid upgrade costs such as:

- Architectural and civil works designs due to complexity of locations.
- Complex planning requests/consents, including conservation area aesthetics considerations.
- Managing archaeological surveys/constraints.
- Costs arising from working in or on ground which has become contaminated.

The estimated network reinforcement savings associated with a range of future scenarios is explored in further detail in Chapter 8.

4.2.2 Cost Considerations of The Smart Grid Approach

From a systems perspective, the Smart Grid is comprised of three high-level layers:

- Physical power layer (electrical power transmission and distribution);
- Data transport and control layer (communications and control); and
- Applications layer (applications and services).

As such, it is the convergence of three different industries: the electricity industry, the telecommunications industry and the Information Technology (IT) industry. In order to realise full end-to-end Smart Grids, able to run suitable Smart Grid applications from the supplier and/or the distribution network operator all the way down to the customers and vice versa, robust two-way communication networks are required. The emergence of an end-to-end communications layer will be critical for advancing the Smart Grid concept and thereby for realising the potential technical, economical and environmental benefits that may be obtained by this approach. Furthermore, Smart Grids can facilitate the integration of distributed power resources at mass scale, and thus allowing not only data to move in two directions, but also electrical power.

The alternative Smart-Grid approach will therefore mainly include the following asset capital expenditure costs, assuming that significant asset investment deferrals can be realised with regards the need for new transformers and circuits though higher distribution network utilisation:

- A supervisory real-time control system, which can be employed using centralised or distributed control architectures.
- Increase in remotely-controlled/automated switching functionality on the network assets. It should be noted here that some of the existing distribution assets will not be suitable for the new technologies that will be added to the distribution network, which could lead to increased asset replacement costs.
- A common communications medium to integrate the behaviour and actions of all participants in the distribution system.
- Advanced sensors and metering devices for improved real-time data acquisition (including Smart Meters).
- Integrated protection systems that react to network fault conditions, unusual transient behaviour and post-event recovery to allow the system to return back to normal operation (such as auto-reclosers).
- Condition monitoring tools and the use of dynamic equipment ratings to monitor weather conditions in real time in order to improve existing network utilisation.
- Energy storage management technologies.

Clearly, the capital cost related to these assets will mainly depend on the voltage level they will be connected to, their rating under normal and abnormal conditions and other specific technical requirements, such as the level of intelligence required for the control system, the speed and security levels required for the communications medium, the level of intelligence and communication capabilities of the sensors and metering devices etc. In turn, these costs will depend on where network reinforcement due to PiV recharging is required (for example, can lower voltage network reinforcement be postponed or even avoided as a result of higher voltage network reinforcement or due to higher grid utilisation through a smarter approach?) and the investment required will vary with three different parameters:

- Distribution network's maximum coincident demand;
- Number and attributes of network interconnection points;
- Reliability of the interconnection facilities as measured by their first circuit (for maintenance) and second circuit outage conditions under different network operating scenarios.

Additionally, a consumer portal will be required to connect customers and their load/generation/energy storage equipment with energy service and communication entities. In GB, this will be achieved through the establishment of the central data and communications entity (DCC). Apart from the capital costs for infrastructure, as well as costs of equipment and devices, other costs that may be considered include: (i) fuel costs; (ii) labour costs for operations, maintenance, repair and power restoration; as well as (iii) installed costs incurred for Smart Grid support infrastructure and services (such as 'back-room' information technology, for example).

An estimate of the costs involved in developing some of the capabilities needed for the Smart-Grid approach are described in the next Chapter. In particular, this report considers the costs of developing various levels of grid 'intelligence' necessary to enable two different smart PiV recharging control strategies.

5 Costs Associated With Electricity Distribution Network Intelligence Necessary For Smart Piv Recharging Control

Intelligence upgrades are required in order to create a smart grid to gather relevant information from network nodes or equipment with an appropriate frequency, and for monitoring and control. Intelligence upgrades are necessary to limit the scale of network reinforcement but will not entirely mitigate the need for reinforcements. These intelligence upgrades involve gathering relevant data from different points in the network and using this data to control parameters and loads to minimise the impact of electric vehicle recharging.

The scope of this section is illustrated in Figure 5-3. It covers the intelligence infrastructure for the DNO at the secondary substation and smart meter, both in the home and in public charging locations.

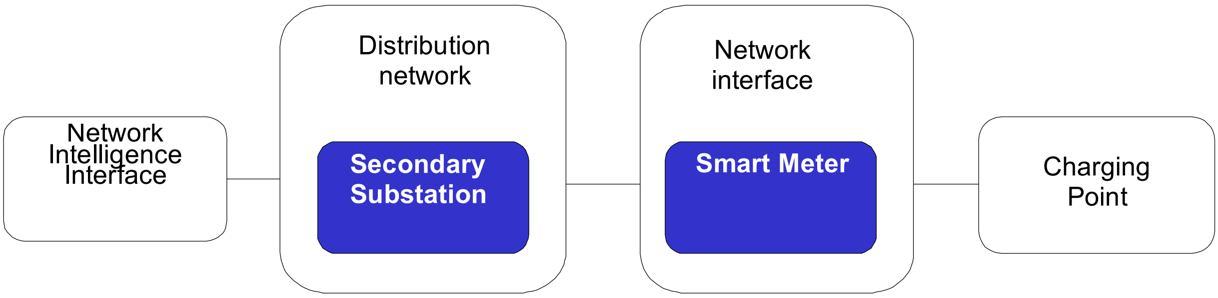


Figure 5-3 : Scope of Intelligence Infrastructure Costs [40]

5.1 Overall System Requirements

5.1.1 Residential Recharging Point and Integration within The UK Smart Metering System

The illustrations below in Figure 5-4 show a variety of views of the electricity smart metering system being currently developed within the UK. The electricity smart meter will communicate with a home ‘gateway’ that will then send and receive data to and from the Data Communications Company (DCC). The DCC will be a common, central actor in charge of the data transmission to authorized parties, as well as some other data storage and data processing functions.

The gateway is represented in Figure 5-4 as a separate device; however it could be an integral module in the electricity meter. The Customer Display Unit (CDU), which for clarity is not included in the illustration below, will be able to display consumption information or other messages through communication with the electricity meter and the gateway and could also be used for prepayment.

This figure shows four options for electric car smart metering:

1. A smart meter dedicated to the electric vehicle, connected just at the interface with the recharging point – this meter is not necessarily the same as the house smart meter.

2. A smart meter dedicated to the measurement of the recharging point feeder, of small size and directly integrated into the domestic consumer unit.
3. A 2-element smart meter, with one element dedicated to the measurement of the electric vehicle feeder, and the other measuring the other loads.
4. A smart meter directly integrated into the vehicle.

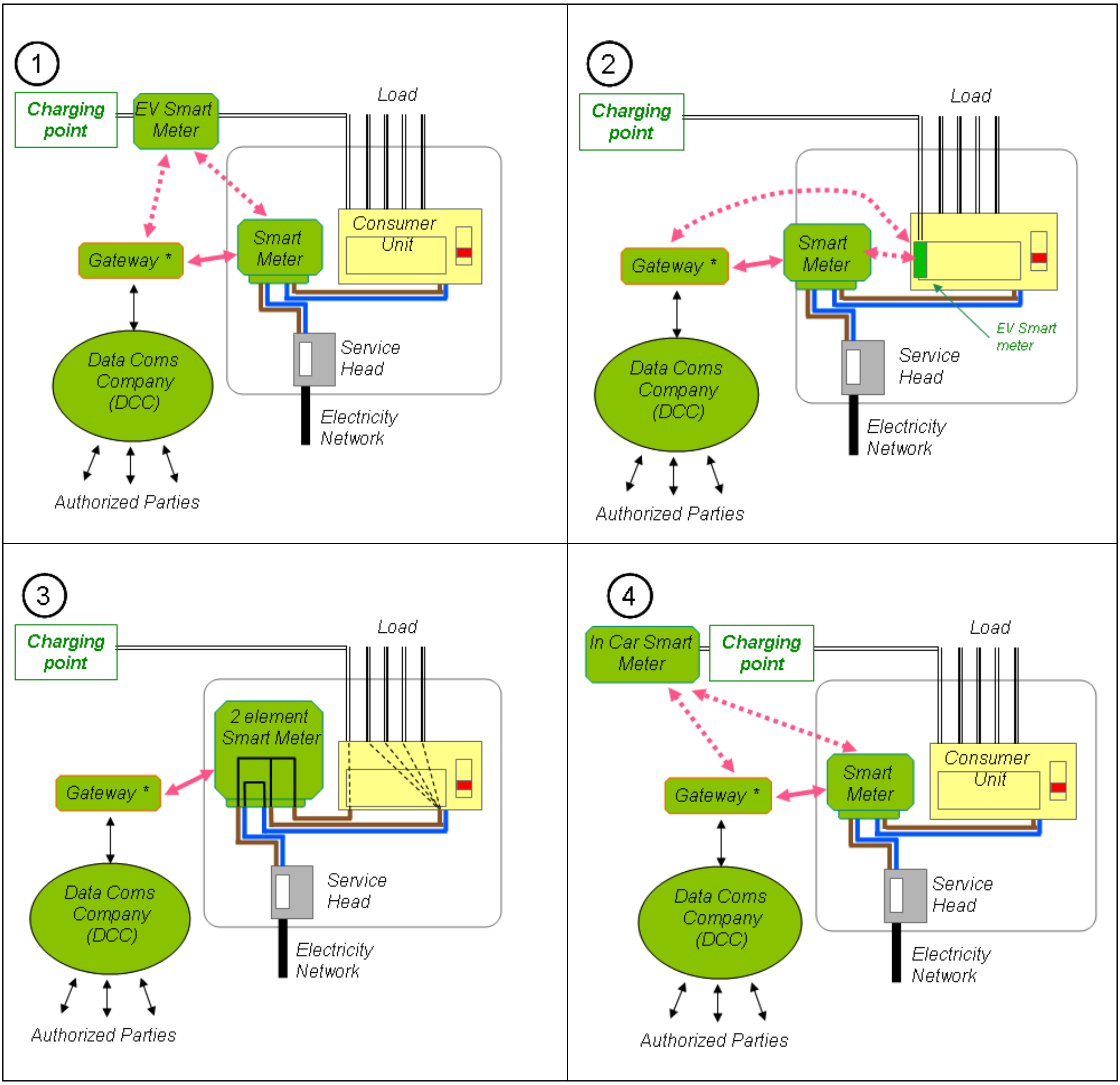


Figure 5-4 : Options for Metering of Residential Recharging [40]

5.1.2 Public Recharging Point

In the case of a public recharging point, the difference from the residential recharging point is that there is no prior metering system installed.

In addition to each of the smart meters associated with each parking charging point, it could be of interest to have a general, three-phase smart meter to collect information for the whole parking area instead of aggregating data from all the individual meters.

The concentration of electricity meters in a car park could be taken into account to share a single communication device between several charging points, using a local communication solution (Powerline communications or radio for example) within the car park. The single communication device would be essentially a 'super-gateway', enabling a set of several meters to communicate with the DCC.

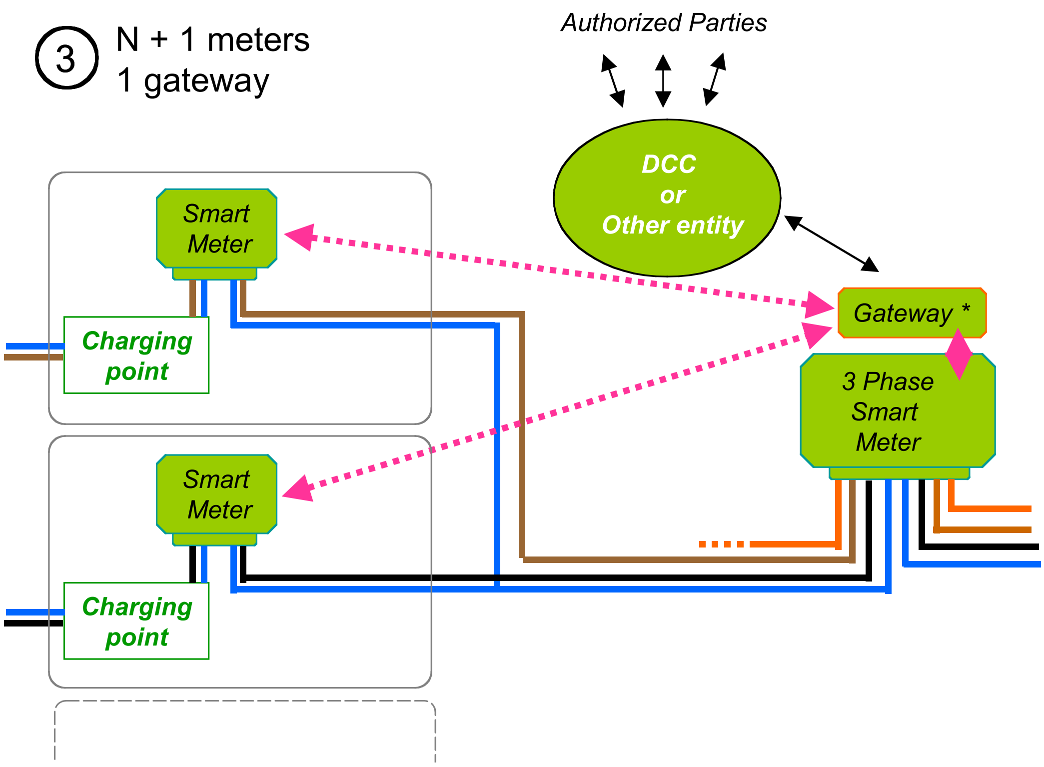


Figure 5-5 : Option for Car Park Recharging [40]

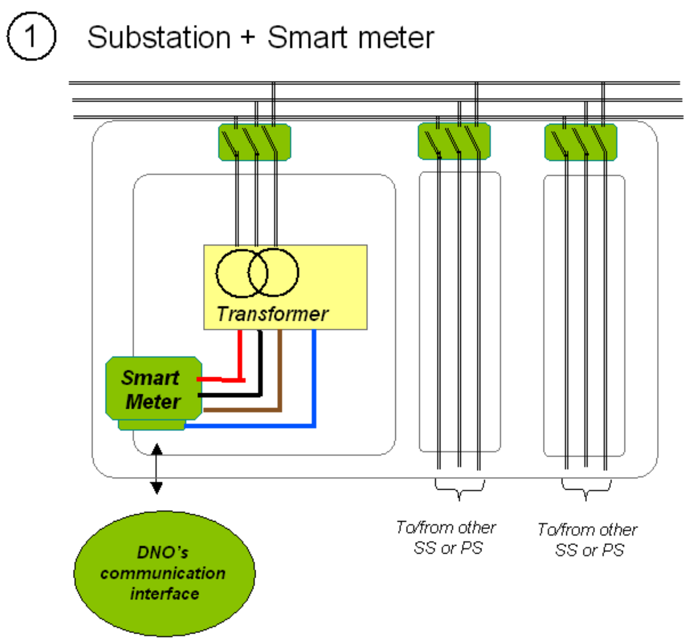
5.2 Distribution Network Upgrades

5.2.1 Secondary Substation Upgrade

Current substation input and output data includes state measurements, status data and control. In addition to these basic measurements, some advanced substations integrate intelligent, electronic devices, in charge of gathering analogue signals such as transformer temperature or relay states. In addition to these basic features, modern transformers can be equipped with more complex and flexible functionality such as multiple voltage levels, many circuit breakers and a large amount of protection and control equipment (voltage and current transformers, relays and SCADA systems).

In order to handle increased complexity within the substation, new devices are required. One device that can be added as a first step towards the 'smart substation' concept is a smart substation meter, as reflected in the first illustration in Figure 5-6. The smart meter will carry out electricity-related measurements such as power factor, active and reactive energy, sag and swell or power outages recording. This multiphase smart meter, located in the substation, will measure accurately the energy consumption within the substation, providing the substation's load profile. This load profile comprises highly valuable information that will permit the development of load control policies as well as quality enhancements, since the network constraints will be properly reflected and taken into account.

Nevertheless, a single smart meter will not be able to provide all the services required for the future. Since large substations can have multiple voltage levels, many circuit breakers and a large amount of protection and control equipment, coupled with highly automated SCADA and communication systems. New and more complex devices may be required. Such highly intelligent and communicative devices are controlled by a central node, the 'substation node' (SSN), capable of orchestrating the commands in an autonomous way, as shown in Figure 5-6 below.



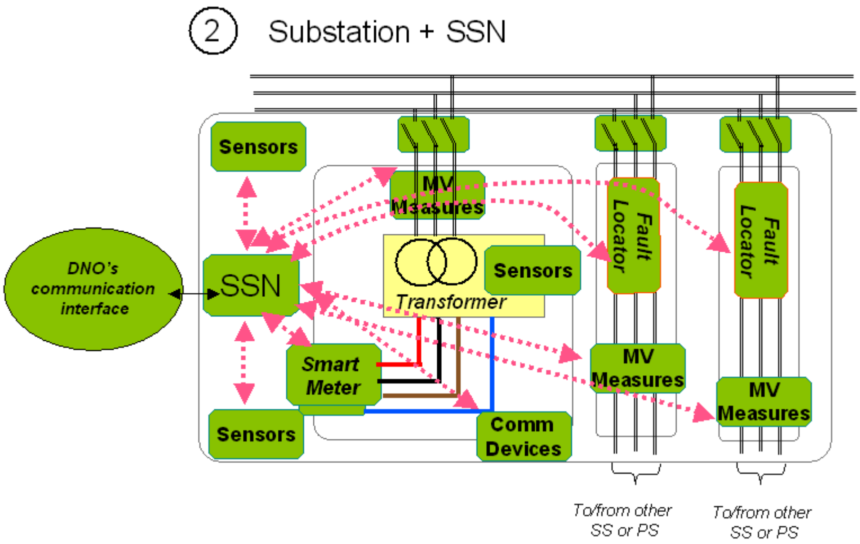


Figure 5-6 : Basic and Complex Monitoring of Substations [40]

5.2.2 The Substation Node

Overall, the SSN gathers and collects all the relevant network information and will be capable of integrating PiVs from a Smart Grid application perspective. The main issue regarding the PiV is its location and availability, since the PiV is by its nature a highly mobile source of demand. Also, the demand curve specifies how much energy is necessary at any time, which is not necessarily directly linked with the PiV users' habits and availability. Furthermore, if the electric car of tomorrow becomes able to export charge, once the feasibility of the 'V2G' or 'V2H' concept is proven, the problem of coordinating all this has to be handled in a harmonious way by the SSN.

The easiest way to manage the PiV impact within the network could be that the SSN would be able to send commands to the PiV infrastructure to regulate their active and reactive power flow to the network. Besides, the advanced smart meter and control system devices installed in the interconnection system of the charging infrastructure, will permit communication with the SSN and provide accurate measurement information. This kind of information will be essential to anticipate the PiV demand within a specific area and implement highly intelligent demand-response algorithms taking account of the network and substation constraints.

Once the substation node is installed in the substation, it could control many of the main functionalities and related control features summarised below:

- LV-side supervision.
- MV-side supervision.
- Transformer supervision and control.
- General supervision: alarm and event management.
- Remote metering management and automation.
- Time synchronization.
- Security and protection.
- Sensor data gathering, fault locators.
- GIS (Graphical Information System).
- Distributed energy generation and E-mobility.

5.3 Focus on Power Quality Monitoring

Quality of electricity is important both for the network operator and for the customers (whose loads can be sensitive to quality problems). As part of the intelligence upgrade required for the electric vehicle, it is important to consider this aspect separately as the charging of electric vehicles may have impacts on the quality delivered to the end-users of a network.

Quality data measured by residential smart meters already installed or to be rolled-out in the coming years are generally limited to:
- Supply interruption (dates and durations),
- Sag and swell.
- Voltage level (which makes it possible to assess the voltage drop on the network).

Measurement of harmonics over the full spectrum from 100Hz to 150kHz could permit the prevention of critical situations and the gathering of valuable information for the design of future, mass-production vehicles (with filters for high-frequency harmonics, for example).

Harmonics recording is beyond the scope of today's residential or PiV smart meter for cost reasons. Basic power quality monitors measuring average data for power quality and harmonics up to 2kHz, range in price from £1,500 to £3,000 with a more advanced device with signal recording capability costing up to £5,000.

To measure the harmonics for the whole frequency range, a disturbance recorder would have to be installed, which would further significantly increase the cost over that of a quality monitor. Thus, measurements of harmonics during experimental work could be carried out at a few selected points in the network at substations, at the charging point for a subset of residential charging customers or, a single measurement could be made in public car parks.

5.4 Cost Analysis

The costs studied here are the equipment costs for:
- Residential metering of a domestic PiV charging point.
- Car Park metering of a public PiV charging point.
- Substation upgrade.

Residential Metering for Charging Point – Equipment Costs	
Option 1 – PiV Meter installed at the home charging point.	**£30 to £60**
Option 2 – PiV Meter in the consumer unit.	**£20 to £40**
Option 3 – 2-element smart meter.	**£5 to £15** Note: this cost corresponds to the extra cost of having two elements in the supplier smart meter instead of one. (i.e. not the full price of the smart meter itself).
Option 4 – PiV meter in the vehicle.	**£40 to £80** (depending on car manufacturer)

Car Park Metering for Charging Point – Equipment Costs for a Car Park Configuration With N Charging Points	
Option – N+1 meters, 1 single gateway	**N times (£30 to £60) + £300 to £500**

For the residential and parking, the installation is expected to be simultaneous with the overall installation of the charging point system. Thus the installation and test cost is expected to be insignificant compared to the equipment cost.

Substation Intelligence Upgrades – Equipment Costs	
Option 1 – LV metering in the substation	£ 300 to £500
Option 2 – Substation Node	SSN : £1,000 to £ 2,500 MV equipment: £2,500 to £4,000 Other (sensors etc.): £1,500 to £2,500 TOTAL : £5,000 to £9,000

The installation cost of LV metering in substation will be very dependant on the characteristics of the substation. The parameters to take into account are the accessibility of the substation, the space available in the substation and the internal arrangement. In most of the case, the installation is likely to be simple and is evaluated at £120. In other cases, when arrangement of the substation does not allow an easy access for the sensor installation, the installation cost can increase up to £300. At the worst case, the installation could be impossible or at a prohibitive cost.

The communication infrastructure required for smart PiV charging control is described in [33]. This intelligent Infrastructure will be required by the DNO to manage the impact and mitigate the risks of the introduction of Electric Vehicles. These requirements include:

- PiV Demand Management, including payment by consumption, variable tariffs, load balancing, real-time/dynamic information to users, physical control of charging locations, data analytics and information about PiV charging demand – to support control, forecasting and investment decisions.
- In combination with Smart Grids and Smart Meters, the intelligent infrastructure will allow the DNO to make reinforcements to the networks in such a way as to minimise costs and improve the ability to meet new demand.

Three levels of intelligent architecture have been suggested [33]. As shown in Figure 5-7 below, communication and interaction will come with the Semi-intelligent Business Model.

In the short term the simple business model will be sufficient while there is a prevalence of domestic charging. The night shifting of the charge can be ensured by a simple night and day meter radio controlled as it currently exists. In the longer term, the night load shifting may not be sufficient to avoid new peaks and network reinforcement cost. More integration will then be required between PiV and intelligent infrastructure to ensure dynamic management of the load.

This will be achievable with further intelligence from the Semi-intelligent Business Model which provides the functionality of demand and load management specifically for PiV charging.

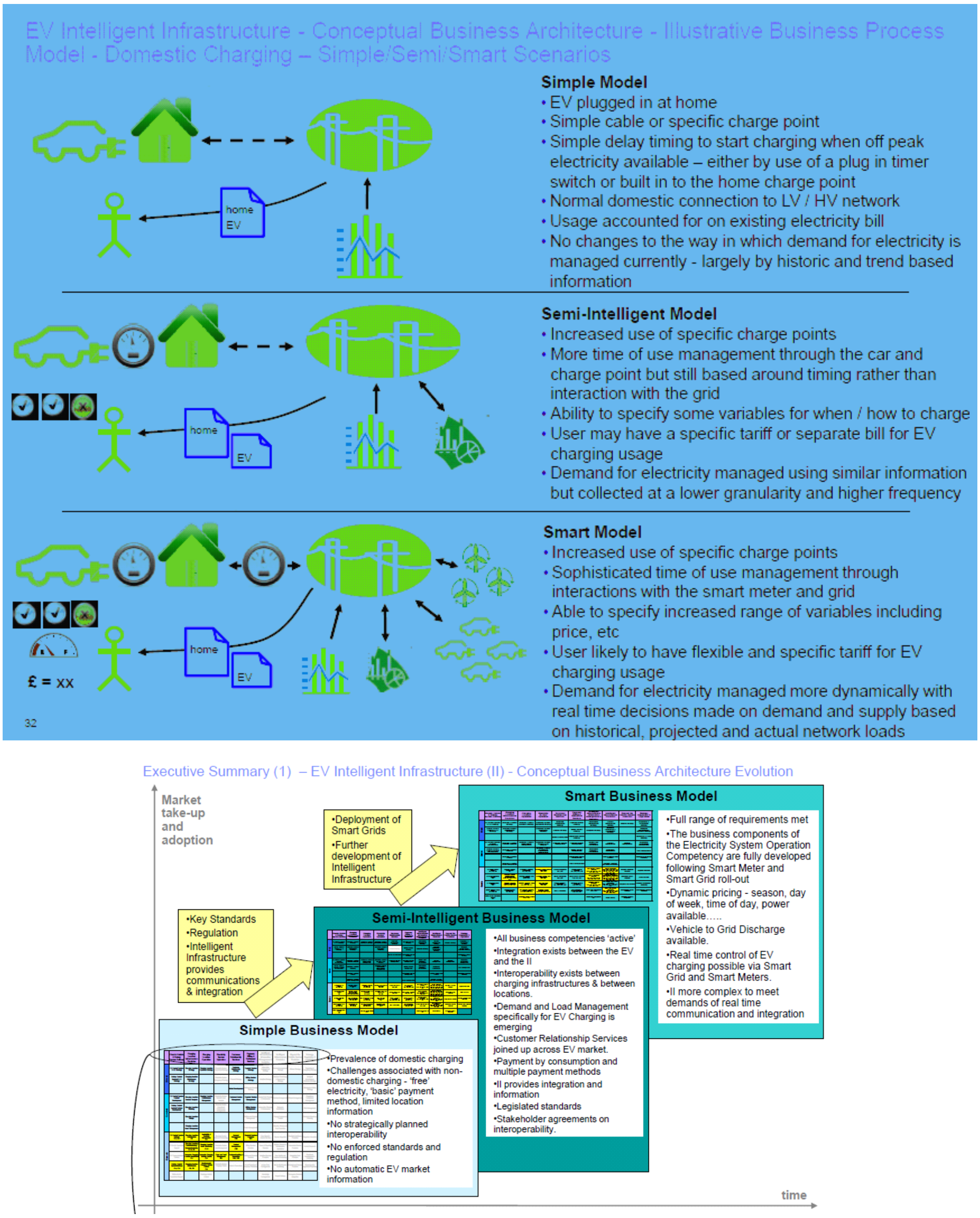


Figure 5-7 : Development of Intelligent PiV Infrastructure [33], [34]

5.5 Smart Charging Costs

In Chapters 6 and 8 scenarios for network reinforcement based on different types of smart charging options are discussed. These smart charging options require differing levels of intelligent infrastructure and therefore entail differing levels of cost. Four options were considered which are summarised below [25]:

- Option O1 – No smart control; Charging occurs after each journey by way of on-street, commercial or workplace charging posts.
- Option O2 – No smart control; Charging after the last journey of the day at home, therefore requiring no specific charging infrastructure.
- Option O3 – 'Smart' charging off-peak during the night, optimised in relation to national demand.
- Option O4 – Fully 'smart' charging with demand optimised with respect to both national and local networks.

5.5.1 Intelligence for Overnight Charging (Option O3)

The cheapest and the most expensive ways of achieving overnight charging option 03 are estimated as follows:

- 'Voluntary – By Default' Option: the PiV owner has a modern dual-tariff meter (and is signed up to the dual tariff), and a domestic PiV charge point installed with a built in timer and override switch. The cost of intelligence in this case is zero.
- 'Centrally Enforced – 2-Way Communication' Option: the PiV owner has a domestic PiV charge point installed with communications capability. The unit communicates to a central control point which controls charging. This option requires the same underlying infrastructure as the fully smart option (O4), but the logic at the central control point is very simple. This could be considered as the first step in implementing the fully smart option (O4). Cost of intelligence therefore comprises:
    - At consumer charge point: communication capability is included in the cost of a wall box as specified in SP2/E.ON/05,
    - For communications: it is assumed that the cost of communications is already provided as part of having a Smart Meter (SP2/IBM/28),
    - For central control:
        - Development of intelligent infrastructure forecasting functionality – £56m for seven GB DNO companies, investment pattern repeated every 10 years; DNOs may have to invest earlier than they possibly think due to peakness of PiV usage in particular locations; investment is over a three year period starting 2013,
        - Development of a bespoke scheduling application with simple logic – between £28m and £56m for seven GB DNO companies. Recurring DNO costs (cost of operation) will be a small fraction of that required for Smart Meter/Grid and hence will be absorbed by those initiatives; investment is over a three year period starting 2015,
        - For additional equipment at the distribution substation – £50m. This was based on 1% of substations (approx 6,000) needing the additional £9k Substation Node (as specified in EDF/05), and this would be needed within the next five years to cope with specific locations, particularly areas of London. Thereafter the cost of intelligence in substations would fall under Smart Grid initiatives.

5.5.2 Intelligence for Fully Smart Charging Option O4

Within this option the PiV owner needs to have a domestic PiV charge point installed with communications capability. The vehicle and consumer communicate respectively to a central control point:

- Amount of energy required to fill the battery.
- User constraints i.e. when the vehicle is planned to be used next.

This data is used to produce an optimised charging schedule. It is assumed that this option would build on the infrastructure put in place for the 'Centrally Enforced 2 Way Option' above and that this sort of functionality would be provided in the Smart Evolutionary Phase when Smart Meters and Gateway Devices have been rolled out – i.e. that the communications infrastructure is in place for Smart Meters and can be used to control charging activity (SP2/IBM/28).
Cost of intelligence is then estimated to comprise:

- At the consumer charge point.
  - Communication capability is included in the cost of a wall box as specified in SP2/E.ON/05.
  - Development of a small application which allows the vehicle and user to supply the necessary data is already included in the cost figures for PiV OEMs (£5m – £8m) and Charging Infrastructure Provider OEMs (£5m – £10m) (SP2/IBM/28).
- For communications: it is assumed that the cost of communications is already provided as part of having a Smart Meter (SP2/IBM/28).
- For central control:
  - Development of intelligent infrastructure forecasting functionality – £56m for seven GB DNO companies, investment pattern repeated every 10 years; DNOs may have to invest earlier than they possibly think due to peakiness of PiV usage in particular locations; investment is over a three year period starting 2013.
  - Development of a bespoke scheduling application with complex logic building on 'Centrally Enforced 2 Way Option' above – in total between £49m and £98m for seven GB DNO companies.
  - For additional equipment at the distribution substation – £50m, as above.

Figure 5-8 below summarises this information and shows the minimum (m) and maximum (M) intelligence cost for charging options O3 and O4. NPV values are as follows O3(m) : £0, O3(M) : £498m, O4(m) : £586m and O4(M) : £656m.

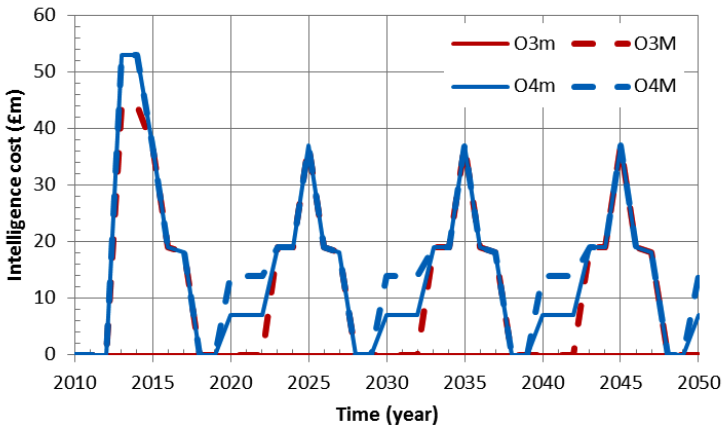


Figure 5-8 : Annual Cost of Intelligence Required for Mitigation Options [31]

6 Impact of Demand Side Management on the Provision of PiV Charging

The smart charging profiles to be discussed in Chapter 8 analyse the network reinforcement costs associated with PiV charging, and assume scenarios where electricity demand is flexible and PiV owners are happy to forgo control of the time of vehicle charge in return for a more cost effective charging regime. Significant market changes are required in Great Britain to arrive at a point in the future where this is the norm on a wide scale. These changes range from technological and economic to societal changes. In terms of the technological changes required, the electricity distribution network needs to be upgraded to the smart grid functionality discussed in earlier chapters to enable visibility of demand on the network. Electricity tariffs that reflect the implications of the time chosen to use electricity would need to be implemented to create price-based demand responsiveness to change electricity usage by customers in response to changes in the prices they pay. Price-based mechanisms include:

- Time-of-use (ToU): a rate with different unit prices for usage during different blocks of time, usually defined for a 24 hour day. ToU rates reflect the average cost of generating and delivering power during those time periods.
- Real-time pricing (RTP): a rate in which the price for electricity typically fluctuates hourly reflecting changes in the wholesale price of electricity. Customers are typically notified of RTP prices on a day-ahead or hour ahead basis.
- Critical Peak Pricing (CPP): CPP rates are a hybrid of the ToU and RTP design. The basic rate structure is ToU. However, provision is made for replacing the normal peak price with a much higher CPP event price under specified trigger conditions (e.g., when system reliability is compromised or supply prices are very high).

These tariffs will need to incorporate a pricing signal from the DNO which could occur through altering Distribution Use of System (DUoS) charges. In the future Real-time pricing and Critical peak pricing would need to become dynamic and localised. In order to send the correct usage message the dynamic load profile on the substation would need to be translated in to a DUoS price. Provided Government policy initiatives [1] are successful in delivering 20% wind generation in the electricity grid mix by 2020, it will not be possible to ensure smart charging through static ToU tariffs. This is due to the fact that when high wind generation occurs at the same time as substation load peaking electricity suppliers will be sending pricing signals to encourage demand increase however this demand increase will not be possible without potentially significant localised network reinforcement. Figure 6-9 shows how this dynamic DUoS price signal might work in the future.

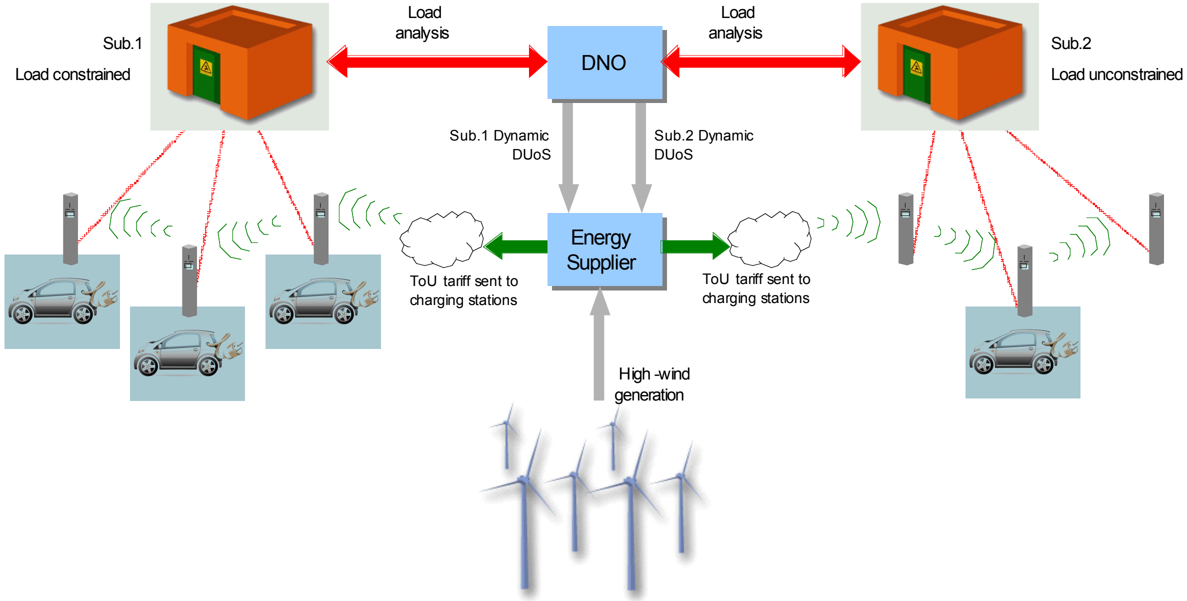


Figure 6-9 : Illustration of Dynamic DUoS and ToU tariffs

Participation by customers in electricity markets in the manner envisaged through the smart charging profiles analysed in Chapter 8 is known as Demand Response. Demand Response allows industrial, commercial and retail customers to participate in electricity markets by giving them the ability to respond to prices as they change over time – either daily or hourly in most instances. Methods of engaging customers in demand response efforts include offering a retail electricity rate that reflects the time-varying nature of electricity costs or programs that provide incentives to reduce load at critical times, such as:

- Direct load control: a program by which the program operator remotely shuts down or cycles a customer's electrical equipment (e.g. air conditioner, water heater, space heating) on short notice.
- Interruptible/Curtailable (I/C) service: curtailment options integrated into retail tariffs that provide a rate discount or bill credit for agreeing to reduce load during system contingencies.
- Demand Bidding/Buyback Programs: customers offer bids to curtail based on wholesale electricity market prices or an equivalent.
- Emergency Demand Response Programs: programs that provide incentive payments to customers for load reductions during periods when reserve shortfalls arise.
- Capacity Market Programs: customers offer load curtailments as system capacity to replace conventional generation or delivery resources.
- Ancillary Services Market Programs: customers bid load curtailments in International Standards Organisation (ISO) markets as operating reserves.

As mentioned above, in addition to the technological and commercial changes required, societal changes are also required. Significant education and engagement is required to explain to retail customers that the time they decide to use electricity in the future will have a major impact on the cost of that electricity provision. Failure to effectively engage with customers can potentially make smart grids very difficult to implement in countries with robust democratic frameworks. Smart grid projects in both Holland [35] and the United States [36] have failed to achieve the benefits anticipated as a result of failed consumer engagement initiatives. The cost of such engagement has yet to be fully evaluated nor has the business case for supporting this cost as yet been justified.

It is likely to be significant and this cost must be added to the costs mentioned in Chapter 5 regarding intelligent infrastructure in evaluating smart grids and evaluating the network reinforcement cost that can be mitigated by smart grids.

Assuming that such customer engagement has taken place and achieved widespread acceptance of the concept of foregoing control of time of vehicle charging, it is possible to manage a number of loads on the network in a manner that optimises network assets in a complimentary manner. Table 6-6 below summarises a range of potential customer-side mitigation measures.

Option	Strengths	Weaknesses
Smart EV Charging Control	Potentially very significant benefits improves network utilisation.	Information about intended use of PiV needed; Communication/intelligence infrastructure required. Robustness to be established.
Micro-CHP	Potentially significant benefits.	Non controllable as electrical output is driven by heating requirements.
Micro-CHP with Heat Storage	Potential benefits.	Benefits will be already achieved by smart voltage and PiV charging control; Communication/intelligence infrastructure required. Robustness to be established.
HP with Heat Storage	Potentially significant benefits.	Communication/intelligence infrastructure required. Robustness to be established
Smart DE7 Heatload Control	Might provide the additional benefit if smart PiV charging control is implemented.	No recorded benefit; If heating is done by heat pumps this option will not exists anymore. Communication/intelligence infrastructure required. Robustness to be established.
Smart Appliances Control	Provide limited benefits as it can mitigate peak increase when peaks are very prominent.	Benefits achievable on small proportion on networks – semi urban. Value and benefits of this option likely to reduce with increase in application of smart voltage and charging control and other DSM measures that may flatten the load profile.

Table 6-6 : Applicability of Reinforcement/Mitigation Options [32]

Modelling by Imperial Consultants of the impact on network reinforcement cost of these mitigation options is briefly described below to demonstrate the potential on various different distribution network types. A range of 'representative networks' are used that characterise the typical distribution network types mainly found across Great Britain, such as densely connected, underground urban networks and rural, overhead-based networks. The concept of representative networks and their use in the model is explained in more depth in Chapter 7.

6.1 Smart PiV Charging Control

By way of example, the diagram below shows the impact of smart charging control on estimated network reinforcement cost per consumer for a representative network type characterising a typical sub-urban distribution environment ('sub-urban-1'). For a particular fixed penetration of PiVs, four different charging control options were considered, as described earlier:

- O1 – No smart control; Charging occurs after each journey by way of on-street, commercial or workplace charging posts.
- O2 – No smart control; Charging after the last journey of the day at home, therefore requiring no specific charging infrastructure.
- O3 – 'Smart' charging off-peak during the night, optimised in relation to national demand.
- O4 – Fully 'smart' charging with demand optimised with respect to both national and local networks.

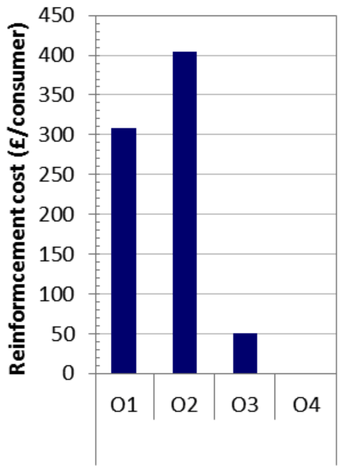


Figure 6-10 : Modelled Network Reinforcement Cost for Various Piv Charging Control Options (Adapted From [32] Figure 7 HVP)

As shown above, allowing uncontrolled charging, either during the day (O1) or at the end of the day (O2) result in much higher reinforcement costs compared to off-peak (O3) or locally optimised, smart charging (O4) for this network type. It should be noted that this is not always the case for all types of distribution network – for example those characterised by peak-demands during the night may not benefit if off-peak PiV charging is also applied. This is discussed further in Chapter 8 for all representative network types.

6.2 Micro-CHP

Although micro-CHP operation will be driven by heat demand, there may be synergies with PiV demand, for example on arrival home in the evening when home-heating traditionally kicks-in and PiVs are set to charge. In this situation, the locally generated electricity may reduce the demand on the substation, reducing reinforcement costs.

Using the model described later in this report, the diagram below shows the estimated impact on reinforcement costs of various penetrations of micro-CHP for another representative network type, 'semi-rural-1'. A peak output of the micro-CHP unit of 1.1kW has been assumed, for penetrations of zero, 40%, 70% and 100%. For the purposes of this illustrative example, PiV charging is assumed to occur at the end of the day as per option O2 described above for the same fixed PiV penetration.

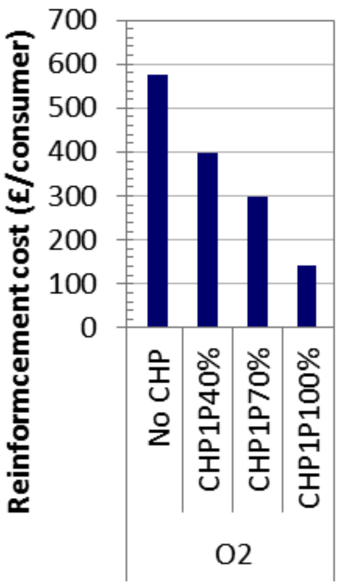


Figure 6-11 : Modelled Network Reinforcement Cost for Various Micro-CHP Penetrations and Piv Charging at the End of the Day (Adapted From [32] Figure 11 HVP)

The diagram shows that reinforcement costs per consumer for this representative network area type are steadily reduced as the penetration of CHP units increases. This is predominantly due to reductions in violations of thermal voltage constraints as network demand reduces. This suggests there are potential benefits in the adoption of CHP to mitigate reinforcement costs, however as before, this will not be the case for all types of network configuration.

The model itself and the impact of a range of these demand-side mitigation options, including the adoption of heat-pumps, are described in further detail in Chapters 7 and 8.

7 Modelling the Impact of PiVs on the Distribution Network – Overall Model Description

To enable an assessment of the reinforcement costs on Great Britain's (GB) distribution networks resulting from PiVs, a model has been developed by Imperial Consultants that calculates aggregated peak demands, and estimates the network reinforcement costs required to enable this new demand. The model allows costs to be calculated for individual 'postcode areas' and for a range of scenarios defined by input variables, such as the number of PiVs and charging profiles expected. A GB-wide reinforcement estimate can also be obtained by summing reinforcement costs across a number of postcode areas that represent the whole GB distribution network.

In order to facilitate this GB-wide assessment, a reference network approach is taken which disaggregates the entire GB distribution network into a combination of only eight 'representative network' types. These eight representative networks effectively characterise the main types of network found across Great Britain, for example urban and rural. By understanding the reinforcement costs and impact of PiVs on these individual representative networks, the overall cost of reinforcement across Great Britain can be estimated by combining a large number of representative networks that sum to characterise the whole GB distribution network.

This chapter aims to describe the overall methodology behind the model and how it can be used to estimate reinforcement costs. At the highest-level, the model developed can be described in three main functional blocks, as shown in Figure 7-12.

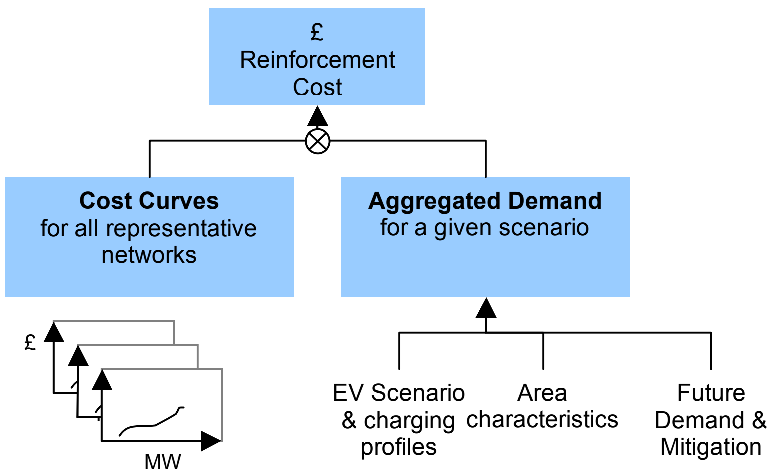


Figure 7-12 : High-Level Model Description

At the heart of the model are 'cost-curves' for each representative network that define the reinforcement costs required as a function of network peak demand. Development of these curves is described in more detail below in Section 1.1.2.

The second aspect to the model is the calculation of the aggregated demand associated with a particular PiV scenario. This is obviously dependent on a range of input parameters such as the number of PiVs, expected recharging behaviour and the network characteristics of the area being modelled. This peak demand, in conjunction with the cost-curves, is then used to identify the likely total reinforcement cost required.

7.1 Relating Peak Demand to Reinforcement Cost using Representative Networks

7.1.1 Representative Networks

As described earlier eight 'representative networks' were developed by Imperial Consultants that broadly characterise all the typical network layouts and configurations observed across Great Britain. This work was informed by an Energy Networks Association (ENA) Workshop and the provision of high level data associated with GB distribution networks. The representative networks are summarised in Table 7-7.

Representative Network Name	Characteristics
Rural 1	• Driven largely by customers on unrestricted domestic tariffs and large industrial demand. • Small morning peak.
Rural 2	• Driven by domestic consumers on economy-7 tariff. • Night time peak demand.
Semi Rural 1	• Mix of domestic consumers and small non-domestic loads. • Relatively flat demand profile.
Semi Rural 2	• Influenced by large non-domestic consumers. • Peak demand during the day, but high night-time load due to economy-7 consumers.
Sub-Urban 1	• Dominated by domestic-unrestricted consumers • Peak demand during the day
Sub-Urban 2	• Driven by non-domestic consumers • Higher peak demand during the day
Urban 1	• Dominated by domestic and small non-domestic load. • Moderate day-time peak.
Urban 2	• Influenced by fewer large non-domestic customers. • Moderate day-time peak.

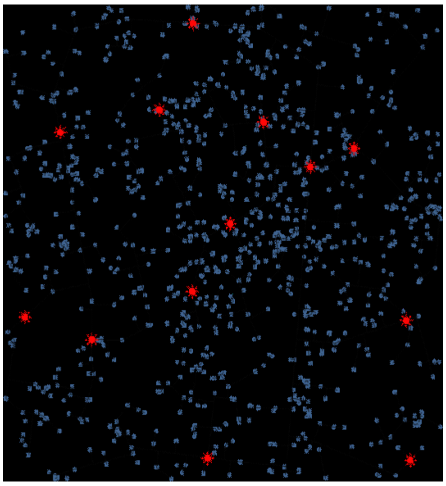
Table 7-7 : Representative Networks and Summary of Characteristics

The representative networks have been selected to reflect specific consumer mixes and layouts associated with different network areas which, in combination, can accurately reflect the aggregate GB distribution network. Key design parameters incorporated include the geographic area, consumer density, the LV and HV density (in terms of cable lengths per km^2) and distribution transformer density. Five categories of consumer were used to define the consumer mix for a particular representative network: domestic-unrestricted, domestic economy-7, small non-domestic, large non-domestic and HV large demand. The mix across these categories was then used to determine the daily demand profile. For further detail see [37], [38], [39].

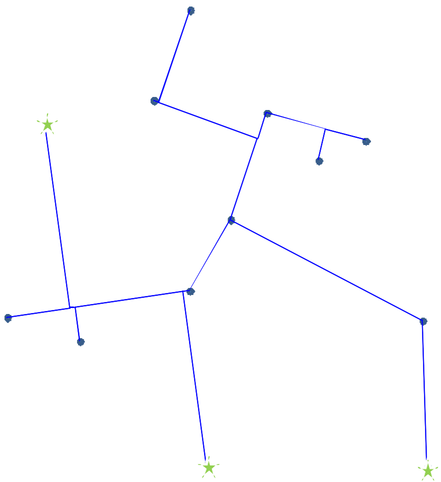
In particular it is important to understand the existing demand patterns in localised network types in addition to uptake rates, as different PiV recharging strategies are likely to result in significantly different reinforcement requirements. For example a recharging strategy that increases load during the night will likely trigger greater reinforcement costs for an area that is already characterised by overnight demand peaks.

The physical design of these networks was achieved using fractal techniques which generate a range of statistically similar networks based on a given customer density. The use of statistically similar models and representative networks means that results are applicable to all networks with similar characteristics. This removes the need for real network models for the whole of Great Britain, and allows the aggregation of these network areas and costs to estimate the full GB-wide picture. For each particular representative network, algorithms and load-flow analysis were used to generate an overall LV and HV network design, including the positioning of substations and the size of underground cables or overhead lines required in order to meet Engineering Recommendation P2/6 [15] security of supply requirements.

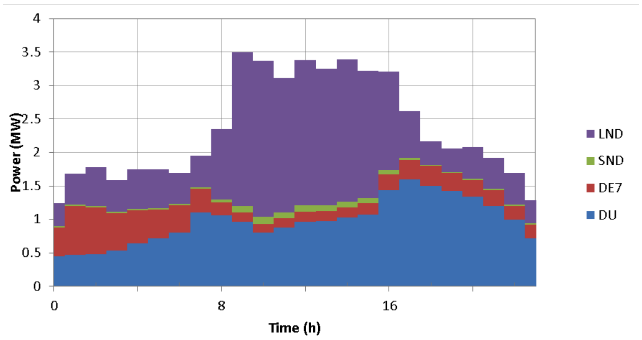
The results of this work are specific LV and HV network designs and associated daily aggregated demand profiles for all eight representative networks, examples of which are shown below for just the ‘Rural 1’ and ‘Urban 1’ networks. Distribution substations are represented by the red stars, with blue dots representing consumer loads. In the HV network diagrams, green stars represent Normal Open Points (NOPs).



LV Network Design



HV Network Design



LV Aggregated Demand Profile

Figure 7-13 : ‘Rural 1’ Representative Network [38]

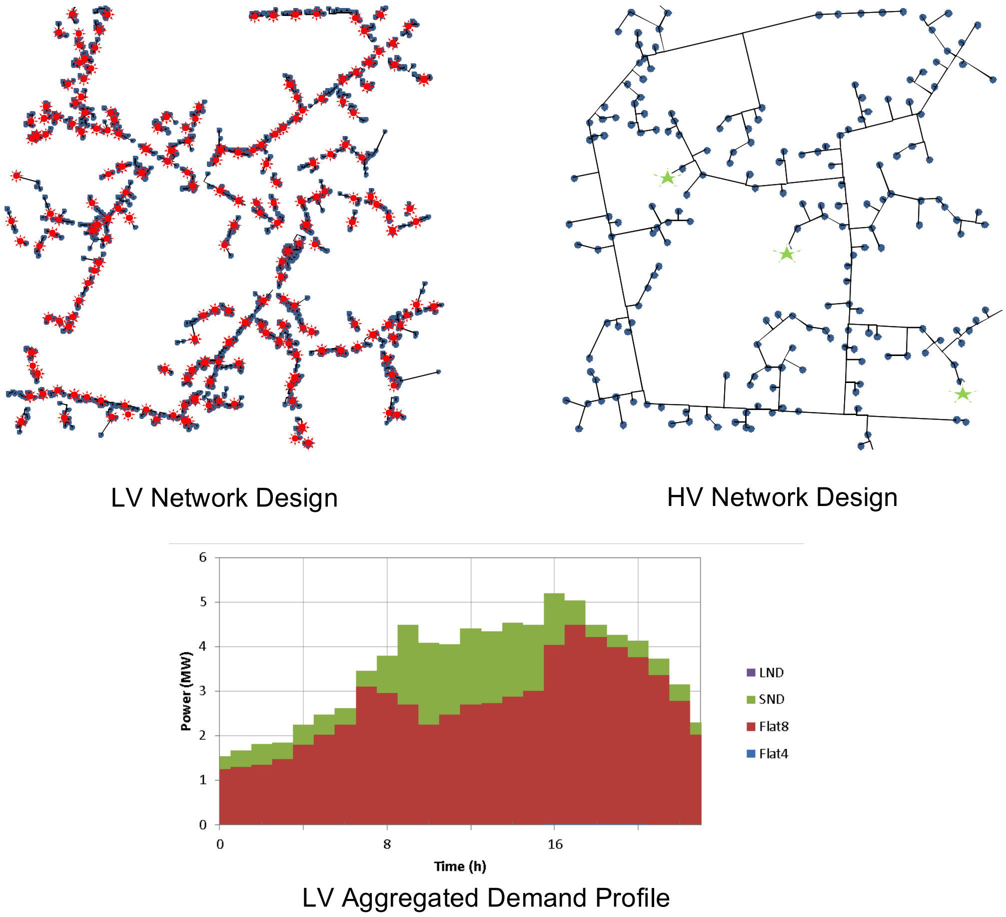


Figure 7-14 : ‘Urban 1’ Representative Network [38]

7.1.2 Network Reinforcement Cost Curves

Using the eight sets of representative designs and demand profiles described above, the reinforcement costs to support various demand increases from PiVs were assessed using power flow analysis techniques and average Ofgem unit costs including materials and labour. Consistent with the algorithms used to develop the designs, the investment options assumed available in the model are:

- Reinforcement of distribution substations.
- Addition of underground cables or overhead lines in order to mitigate violated voltage and thermal constraints for P2/6 compliance.

Over 10,000 individual case studies of this type were carried out to predict the necessary reinforcements and associated costs for each representative network for a range of increased peak demands and differing distributions and types of recharging points across the network.

These results formed the basis of the 'cost-curves' developed for the overall model which, when interpolated using a best-fit trend line, provide a way of estimating the network reinforcement cost as a function of network peak demand. For each representative network, three cost curves were generated:

- The cost of LV network and distribution substations upgrade per customer by peak demand.
- The cost of LV network and distribution substation upgrade if voltage control is applied in the LV network.
- The cost of the HV network upgrade.

An example of the set of three 'cost-curves' developed for the 'Semi-rural 1' representative network is shown below in Figure 7-15.

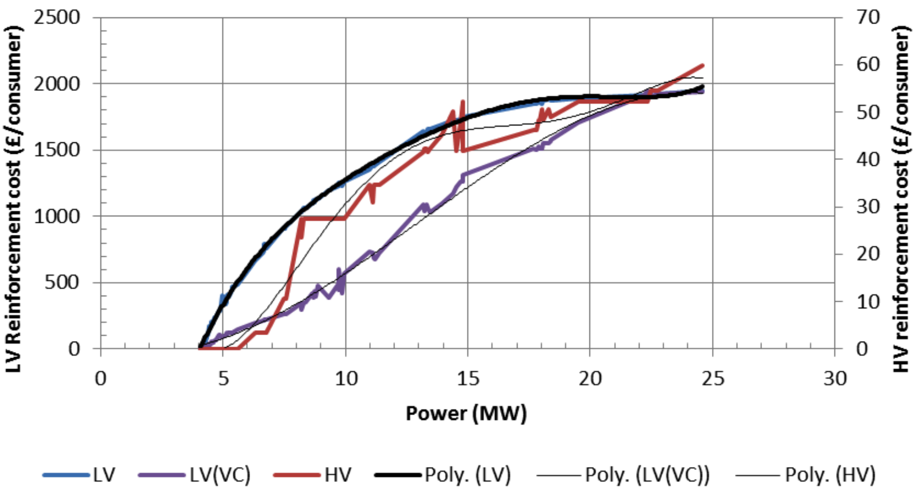


Figure 7-15 : 'Semi-Rural 1' Network Cost Curves [41]

These sets of curves, along with the daily demand profiles previously described, provide a full set of resources for each representative network that can be used to estimate reinforcement costs for any particular peak demand for any postcode area. For example, for an area with a customer density in-between two particular representative networks, a weighted combination of the results from analysis of these two representative networks would be used [39].

7.2 Estimation of Network Reinforcement Costs

To estimate the network reinforcement costs for a particular postcode area, a range of input parameters are entered that describe the characteristics of the network area and PiV penetration for the scenario being assessed.

7.2.1 Scenario Input Parameters

The input parameters used to define a particular scenario are as described below [41] and can be entered for each year from 2010 – 2050 to allow trends in costs to be evaluated:

Inputs for Defining Area Characteristics

Postcode Sector Area
The geographic size of the area for assessment in km^2

Number of Consumers
The number of LV connected customers in the area.

Inputs for Defining Demands due to PiVs

Recharging profiles for PiVs
The maximum aggregated daily recharging profile in kW on an hourly basis for an PiV for each year of the model. The model allows four different profiles to be entered, to allow a range of different recharging locations to be represented, such as domestic, workplace, public car-park and on-street recharging.

Number of PiVs
The number of PiV recharging points across the various recharging locations. Different distributions can be entered for the following recharging locations for each year of the model:

- Number of registered PiVs – Used as a proxy for the number of domestic recharging points.
- Number of workplace car parks with recharging posts.
- Number of public car parks with recharging posts.
- Number of public on-street recharging posts.

Note: for the purposes of this report, assessment of the reinforcement costs has only considered uptake and demand profiles from domestic recharging.

Inputs for Defining Future Demands and Mitigation Measures

Smart Control Penetration
The percentage of recharging that would be available for ‘smart control’ that is fully locally optimised, as per smart recharging option O4.

Heat Pump Uptake and Characteristics
The number of heat pumps installed along with the percentage that are available for smart heat-pump control using storage. This allows modelling of additional future demand due to heat pumps.

Micro-Combined Heat and Power
The number of micro-CHP units installed. This allows modelling of additional future demand due to micro-CHP units.

Smart Appliances Penetration
The percentage of smart appliances available for ‘smart control’.

Smart Economy-7 Heating Control Penetration
The percentage of domestic economy-7 consumers available for smart control of heating load.

Peak Demand Growth
Overall percentage increase in peak demand each year. This allows modelling of the natural growth in overall peak demand seen on distribution networks over time.

Peak Demand Efficiency
The percentage reduction in peak demand due to energy efficiency measures.

Smart Voltage Control Availability
The year when smart voltage control becomes introduced. This allows modelling of scenarios where smart voltage control is introduced at a defined point in the future.

7.2.2 Estimation of Network Reinforcement Costs for a Postcode Area

These inputs are combined in the model to determine an aggregated demand profile for the postcode area. The demand profile takes into account any future demand and mitigation measures entered, such as potential for smart control of heat pumps and appliances. The reinforcement cost for the calculated peak demand is then read from the appropriate cost-curves.

An example of analysis is illustrated below for a network area supplying 2,560 customers, with a customer density of 100 consumers/km^2. Domestic recharging only is assumed, with growth in the PiV daily recharging profile over the period as shown in Figure 7-16 (only intermediate years are shown for clarity).

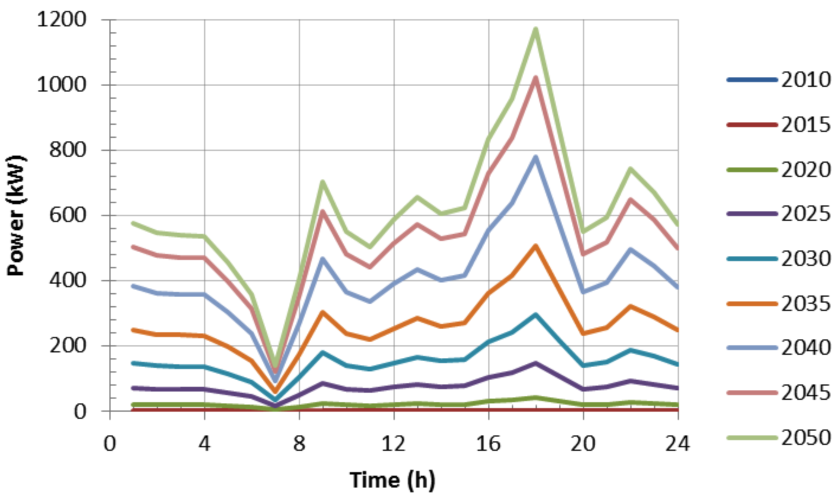


Figure 7-16 : Domestic PiV Recharging Profile (Adapted from [41])

Running the model with these parameters produces the estimated cumulative reinforcement costs as shown in Figure 7-17.

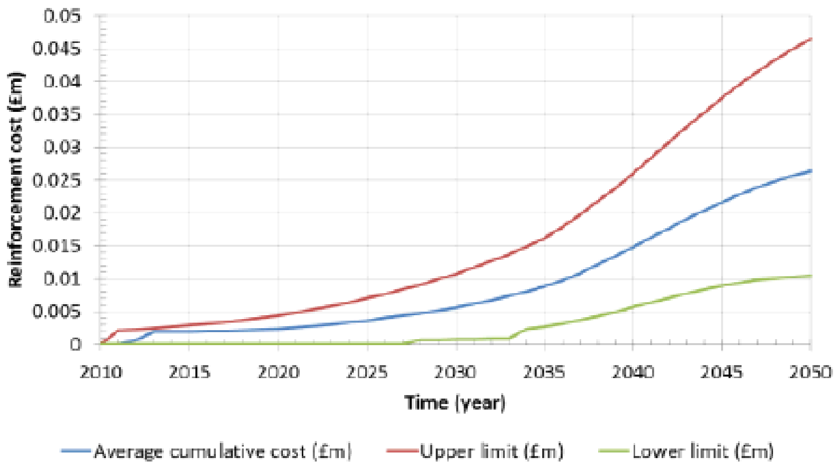


Figure 7-17 : Postcode Area Network Reinforcement Cost [41]

7.2.3 Estimation of Network Reinforcement Costs for a GB-Wide Analysis

A GB-wide analysis of reinforcement costs can be performed in a similar manner to that described above for an individual postcode area. The GB distribution network is assumed to be represented by a set of four disaggregated network types [39] with each pair of representative networks forming a network type. For areas with customer densities in-between two particular representative networks, a weighted combination of results from separate analyses of representative networks can then be used and summed to provide the final result.

Under each of the network types (rural, semi-rural, semi-urban, urban) up to three different sets of input parameters can be entered to allow for variations in the mix of PiV recharging profiles, mitigation strategies and penetration etc. within network types, as shown in Figure 7-18 below.

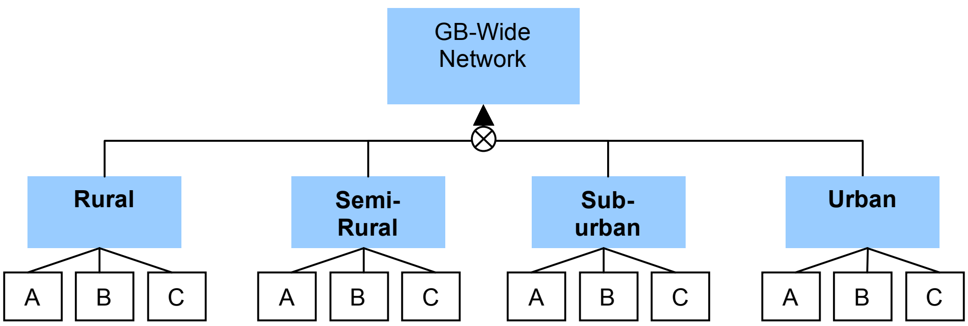


Figure 7-18 : GB-Wide Network Modelling

Once the Element Energy consumer choice model has been completed, the Imperial model will be run in this way using the uptake scenarios identified for each real GB postcode area. This will create the localised network reinforcement cost estimates that can then be summed for a GB-wide view.

8 Case Studies of PiV Impact on the Distribution Network

Using the models described in the previous Chapter, a number of case studies were undertaken by Imperial Consultants to assess the impact of particular PiV scenarios and mitigation options on the likely reinforcement costs required for Great Britain's (GB) distribution networks.

Primarily the impact of the following key variables was assessed:
- The effect of differing levels of uptake of PiVs in GB
- The effect of different PiV recharging profiles expected, including mitigation using smart recharging options.
- The effect of voltage control as a mitigation strategy.
- The effect of concurrent electrification of the heat sector.
- The effect of smart appliance control.

These first two of these variables and the range of values assessed under each driver are described in more detail below.

8.1 PiV Uptake Rates

For the GB-wide case studies, three uptake trends were used that characterise possible rates of electric vehicle uptake within Great Britain. These were defined as 'low', 'base', and 'high' [25] and assumed uptake is split across three population area-types of Great Britain; rural, urban and sub-urban.

The uptake scenarios assume that the growth in PiVs across the population area types is non-uniform, but with the majority of PiVs (around 50%) distributed in sub-urban areas, followed by urban and then rural areas. The final distribution of PiVs by the year 2050 is shown for each uptake case and population area-type in Table 8-8 below.

Pop. Area	Base PiV Case		High PiV Case		Low PiV Case	
Rural	3,770,084	21%	5,652,824	19%	2,442,342	22%
Sub-urban	9,539,308	53%	13,619,232	47%	6,074,566	56%
Urban	4,819,666	27%	9,988,318	34%	2,405,392	22%
Total	**18,129,058**		**29,260,373**		**10,922,300**	

Table 8-8 : Number of Expected Pivs in 2050 By Population Area and Uptake Case [29]

The trend in uptake from 2010 to 2050 for each uptake case by area-type is shown below in Figure 8-19 to Figure 8-21 [29].

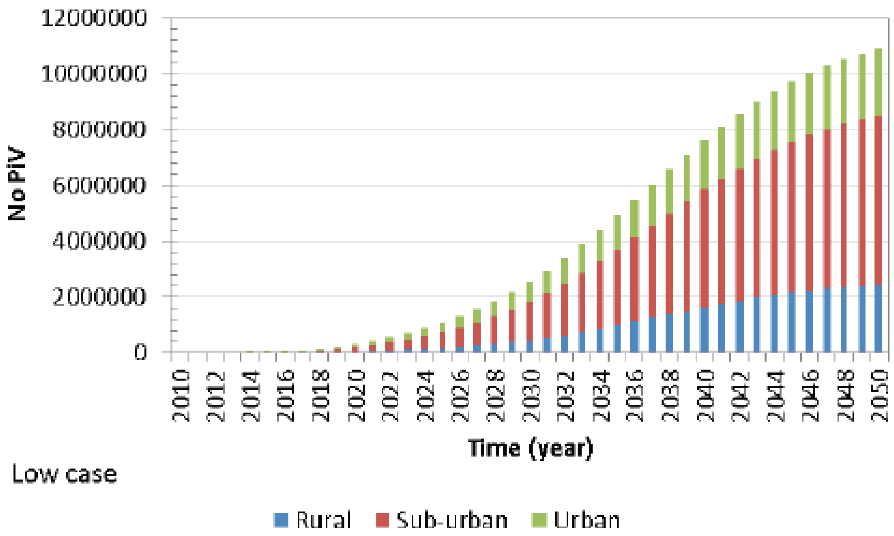


Figure 8-19 : Low Case PiV Uptake Levels by Population Area

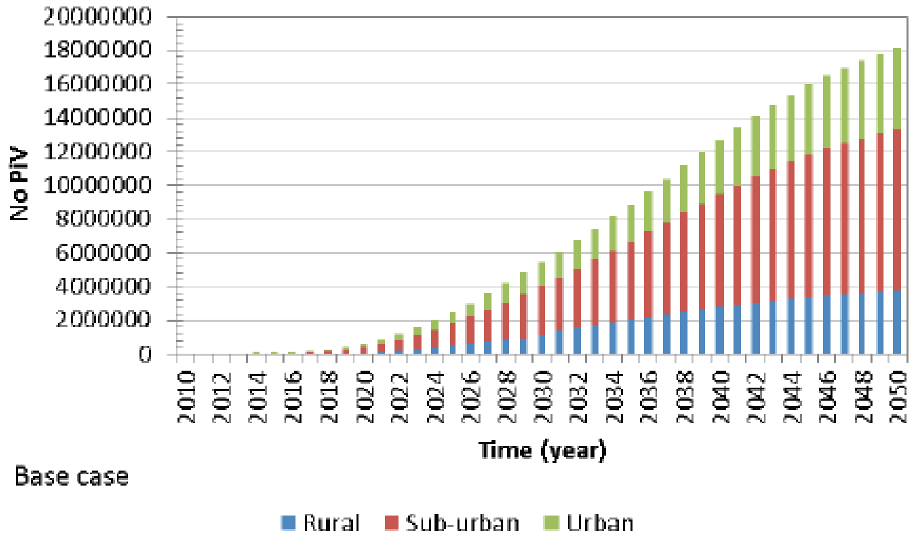


Figure 8-20 : Base Case PiV Uptake Levels by Population Area

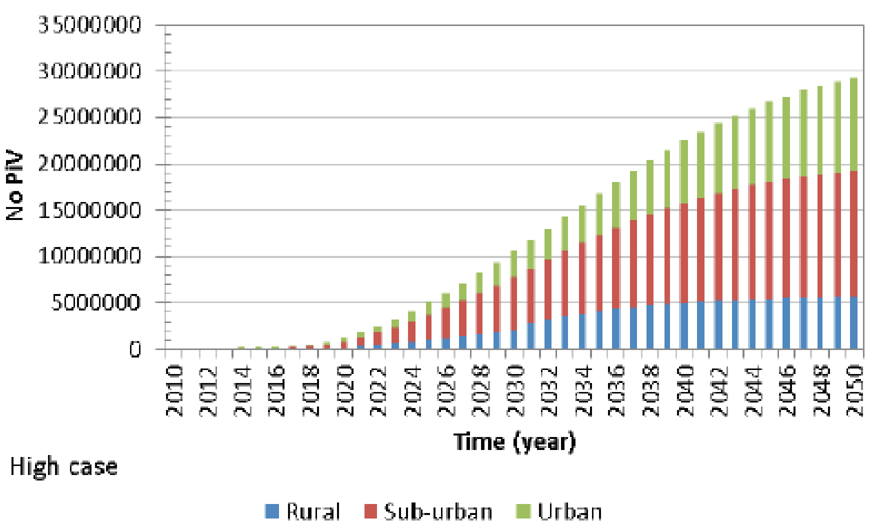


Figure 8-21 : High Case PiV Uptake Levels by Population Area

In order to allow the overall GB-wide network reinforcement cost to be modelled for these scenarios, the three population area-types covering GB as defined by Ricardo [25] needed to be translated to the different representative network types used in the model (urban, sub-urban, semi-rural and rural). This was achieved using a simple transformation matrix which is shown in the table below [29] and used for the remainder of the case studies presented. The total reinforcement costs calculated by the models for the rural, sub-urban and urban areas were then summed to obtain a GB-wide estimate.

Pop. Area \ Net. area	Rural	Semi-rural	Semi-urban	Urban
Rural	52%	48%		
Sub-urban		61%	39%	
Urban			88%	12%

A brief sensitivity study was carried out using different mappings of population areas to network types. This confirmed that using different mappings produced some differences in the relative reinforcement costs across the rural, sub-urban and urban population areas, however the overall GB network reinforcement costs remained similar. Further detail on this can be found in Section 4.6 of [29].

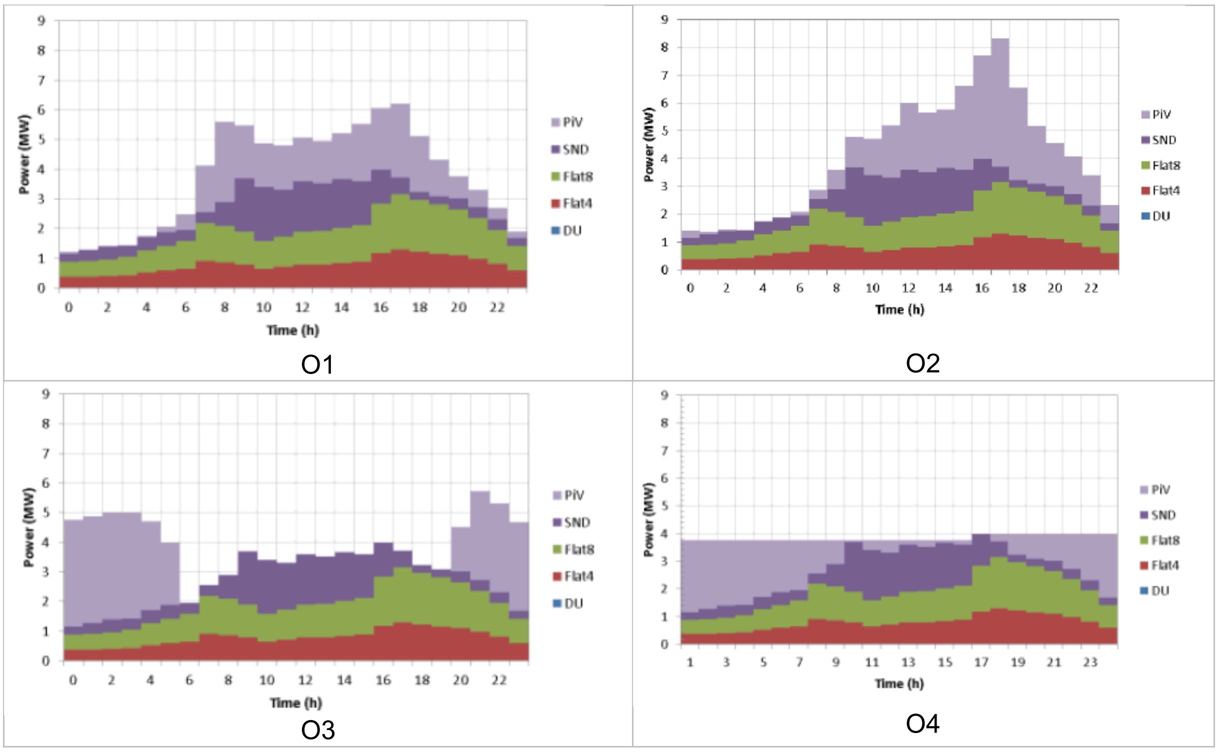
While this approach gives a good estimation of the GB-wide reinforcement costs for the scenarios described, it should be noted that the uptake of PiVs is strongly linked to a number of socio-economic as well as geographic factors, such as income and environmental attitude. More detailed uptake characteristics by actual GB postcode areas will be available once the Element Energy consumer choice model has been completed. The Imperial model has been designed to easily support analysis at this level and can be re-run to create localised network reinforcement cost estimates at the postcode level based on this work. These can then be summed for a more representative GB-wide view.

8.2 Recharging Options

Across the case studies analysed, four potential recharging types have been compared, as introduced earlier:

- O1 – Recharging after each journey by way of on-street, commercial or workplace charging posts.
- O2 – Recharging after the last journey of the day at home, therefore requiring no specific recharging infrastructure.
- O3 – 'Smart' recharging off-peak during the night, optimised in relation to national demand. This would require a basic level of intelligent control infrastructure or basic dual-tariff meters, as described in more detail in Chapter 5.
- O4 – Fully 'smart' recharging with demand optimised with respect to both national and local networks. This would require a more sophisticated level of intelligent control infrastructure, as described in more detail in Chapter 5.

Using the base aggregated daily demand of the 'sub-urban 1' representative network as an example, the impact of these four different domestic recharging profiles on the shape of overall daily demand is shown below. Each diagram shows the additional PiV load (labelled PiV) for a particular PiV penetration for the four different recharging options added to the existing loads of the 'sub-urban 1' network type.



Key:
PiV – Electric vehicle load
SND – Small non-domestic load
Flat 4/8 – Block of 4/8 flat units load
DU – Domestic unrestricted load

Figure 8-22 : Example Recharging Demand Profiles. 'Sub-Urban 1' Network ([30] Fig 10)

Based on the assumption that the capacity of the distribution network is driven by peak demand conditions, recharging profiles based on winter-weekdays were used in the studies as this represented the highest peak load. Different recharging profiles are used for each network area type with demand increasing steadily across the period of modelling, reflecting the consumer mixes and growth in penetration expected in these areas. Throughout the GB-wide case studies, only domestic recharging loads were considered, which provides for more conservative estimates of network reinforcement savings. (The additional demand, reinforcement costs and available optimisation related to workplace and public charge points are not considered).

8.2.1 Impact of Recharging Options on Reinforcement Cost by Network Type

As described earlier, the uptake of PiVs across GB is likely to be non-uniform leading to areas of relatively high penetration in addition to areas of near zero penetration. At an individual postcode area, or representative network-type level, the penetration of PiVs could therefore be significantly higher than the overall GB-wide penetration. Before considering reinforcement costs at the overall GB-wide network level, it is therefore useful to assess the effect of these recharging options at a more granular level on the different representative network types to show the differing impacts that daytime versus off-peak and smart recharging can have.

To illustrate these impacts, specific reinforcement costs were estimated for each representative network type for each recharging option and for two fixed penetrations of PiVs per household (average 0.6 PiVs per household labelled ‘LVP’, and average 1.4 PiVs per household labelled ‘MVP’) [30]. The reinforcement costs are expressed per consumer to allow direct comparison between the different network types and recharging options. The costs are also further broken down in terms of the reinforcement necessary due to thermal constraints (LV-I) and voltage constraints (LV-V) on LV circuits, distribution transformers (HV/LV), HV circuit or primary substation upgrades (EHV/HV) and the costs for voltage levels above EHV and legal and administrative costs (EHV+).

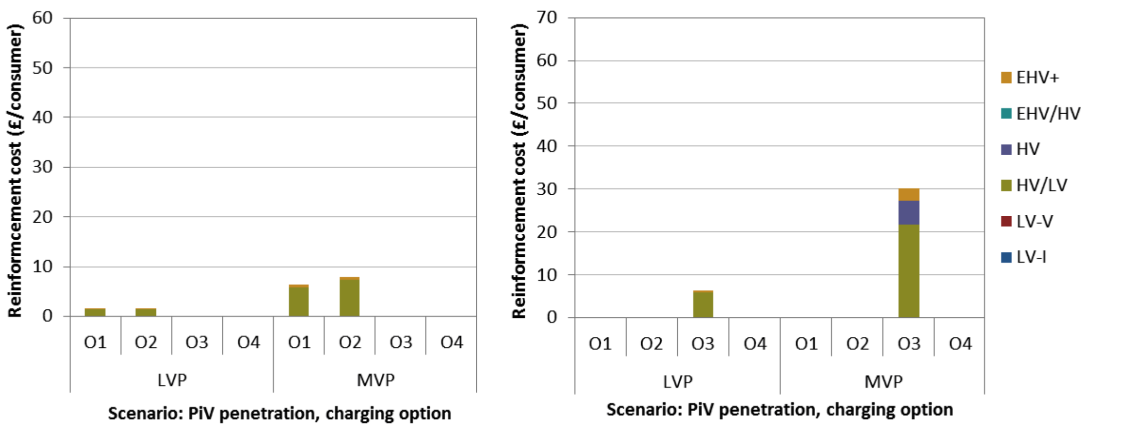


Figure 8-23 : Per Consumer Network Reinforcement Cost by Recharging Option for Rural 1 (Left) and Rural 2 (Right)

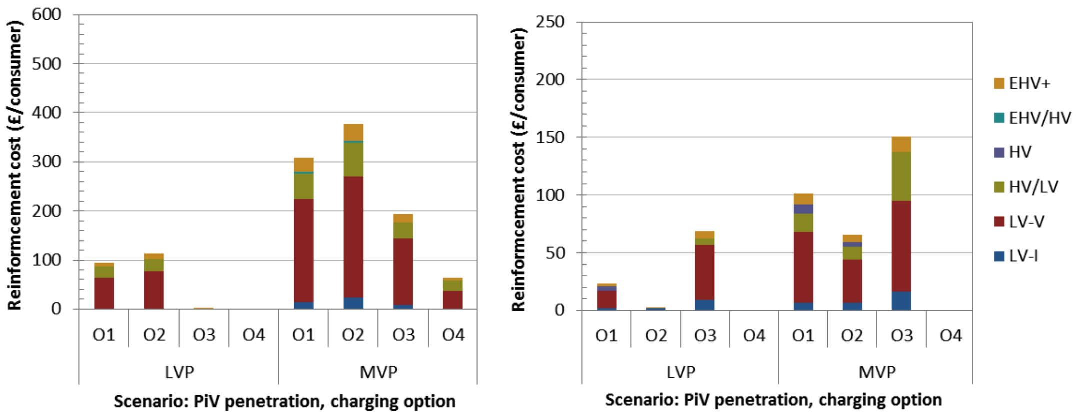


Figure 8-24 : Per Consumer Network Reinforcement Cost by Recharging Option for Semi-Rural 1 (Left) and Semi-Rural 2(Right)

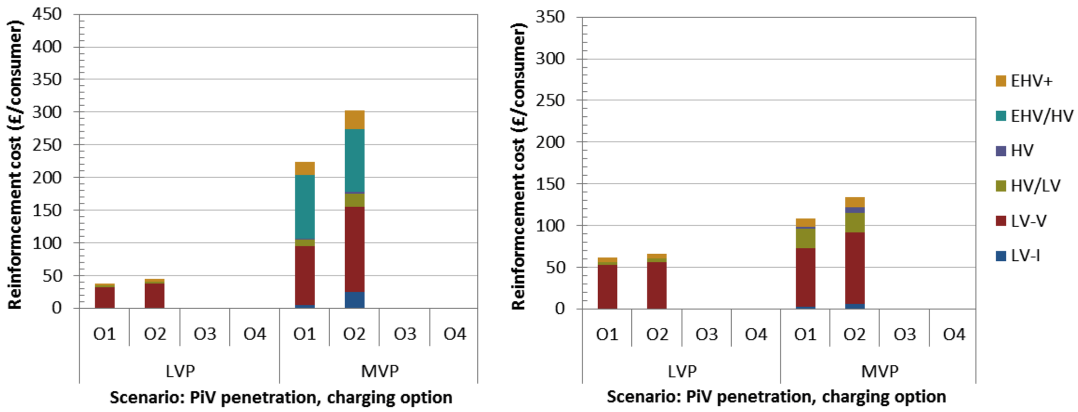


Figure 8-25 : Per Consumer Network Reinforcement Cost by Recharging Option for Sub-Urban 1 (Left) and Sub-Urban 2 (Right)

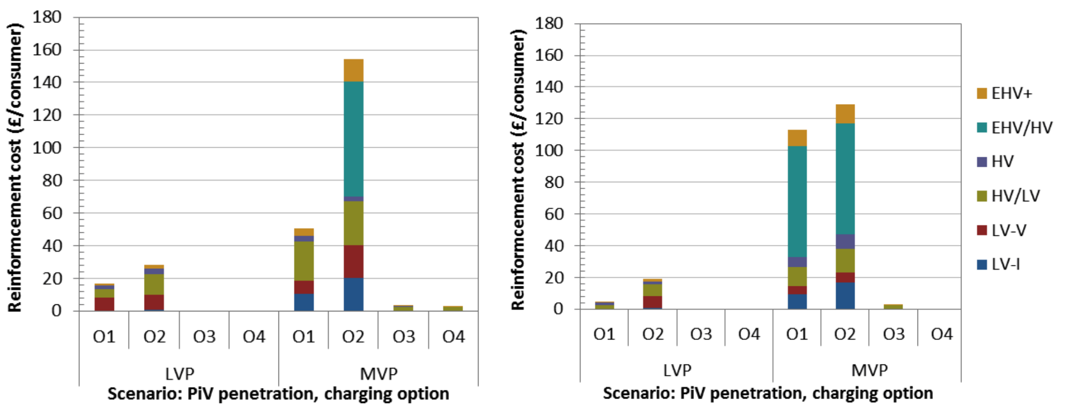


Figure 8-26 : Per Consumer Network Reinforcement Cost by Recharging Option for Urban 1 (Left) and Urban 2 (Right)

For rural type networks it can be seen that if penetration in this area was 0.6 PiVs per household, little reinforcement is necessary when recharging is performed after each journey (O1) or at the end of the day (O2). However for ‘rural 2’ type networks, if recharging overnight (O3) is performed, significant reinforcement would be required due to the dominance of economy-7 consumers which means PiV recharging demand coincides with existing overnight peak demand. If PiV penetration reached 1.4 PiVs per household, reinforcement for 'rural 1' type networks increases significantly when recharging occurs at the end of the day (O2) or during the day (O1) due to coincidence with periods of existing high demand.

For semi-rural type networks reinforcement costs are more significant for the given PiV penetrations, primarily driven by voltage constraints. For 'semi-rural 2' type networks recharging overnight (O3) typically results in the highest network reinforcement costs and so is not recommended for these types of areas. For 'semi-rural 1' type networks recharging during the day (O1) or at the end of the day (O2) typically require the largest reinforcement costs with smarter recharging overnight (O3) or locally optimised recharging (O4) reducing the reinforcement costs required significantly.

For both 'sub-urban' and 'urban' network types, where PiVs are expected to be more prevalent, recharging during the day (O1), or at the end of the day (O2), would require significant reinforcement costs. However these costs can be reduced significantly using either smart recharging overnight (O3) or with full local optimisation (O3).

8.3 Assessment of Select Piv Scenarios

8.3.1 Development of BaU Scenario

From analyses of the impact of various recharging options on the individual representative network types, it was seen that recharging following the last journey of the day (O2) typically resulted in the highest network reinforcement costs per consumer. This recharging option refers to the case where consumers plug in PiVs at home using existing infrastructure, hence no additional recharging infrastructure is required. This scenario, where the traditional approach of simply continuing network reinforcement to accommodate increasing PiV load growth therefore becomes the business-as-usual (BaU) or base case for comparison. For the purpose of these scenario comparisons, the effects of inflation have not been considered.

Using the model, the cumulative trend in estimated network reinforcement costs for this BaU scenario, for the three possible PiV uptake cases is shown below.

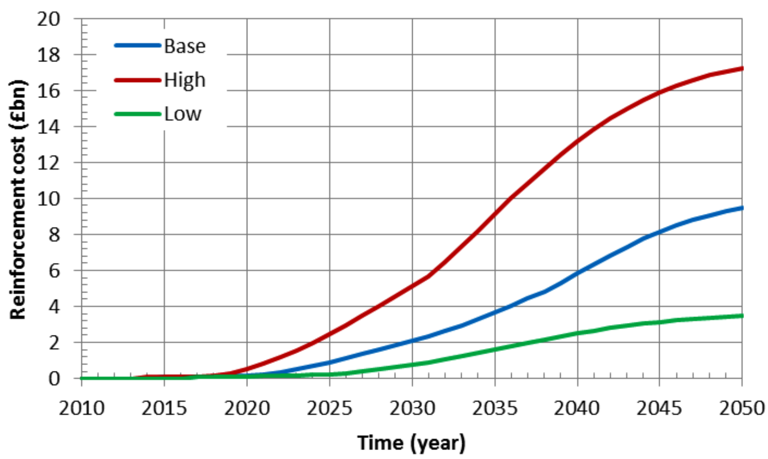


Figure 8-27 : Bau Reinforcement Costs Required for Various Piv Uptake Cases ([31] Figure 5)

8.3.2 Impact of Voltage Control

Taking now only the 'base' PiV uptake case for clarity, the first comparison performed is to assess the overall impact of the introduction of voltage control on the LV network in order to mitigate voltage constraint violations and reduce required reinforcement. In this scenario, it is assumed voltage control is available for all network types from the beginning of the modelling period (2010).

From analysis on representative network types, voltage control is expected to be particularly beneficial in reducing reinforcement across 'semi-rural' and 'sub-urban' type networks, where violation of voltage constraints is a key driver of reinforcement. Further detail on the impact of voltage control of individual representative network types can be found in [30].

Due to the limited experience with distributed voltage control in GB and relatively immature nature of real-time network management the costs of implementation of voltage control at the LV level were challenging to estimate. Initial studies by Imperial assumed a cost of approximately £1k per LV overhead feeder and £2k per underground feeder which allowed estimated cumulative cost profiles to be developed for the overall cost of implementing LV voltage control for a range of scenarios, as described in [31].

These costs are added to the final estimate of network reinforcement cost to provide an overall net cost for the necessary reinforcement. This cumulative net cost for the 'base' PiV penetration case when voltage control is applied is shown in the diagram below against the BaU case.

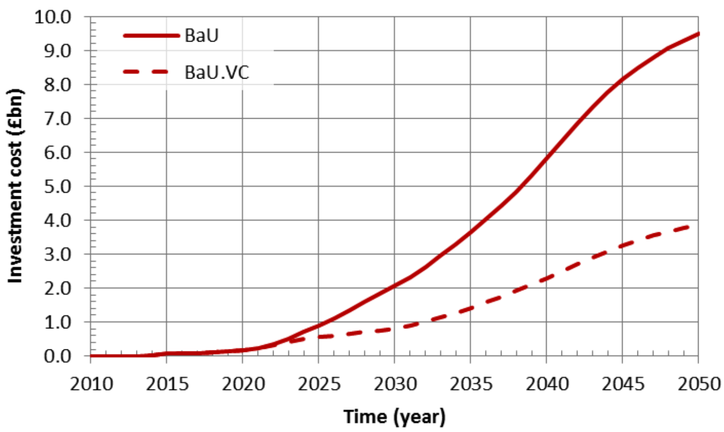


Figure 8-28 : Net Costs with Voltage Control. Base Case PiV Uptake. (Adapted from [31] Figure 15)

The model shows that significant reductions in costs for overall network reinforcement may be possible with the introduction of voltage control.

8.3.3 Impact of Off-Peak Recharging (O3)

As described in Chapter 5, the cost of enabling overnight recharging is dependent on the complexity of implementation. By way of recap, two options were considered:
A dual-tariff approach that required a simple built in timer and override switch.
A more intelligent system with two-way communications to allow dynamic scheduling and central control.

For the purposes of this scenario comparison, the higher estimate of implementation costs have been used and are added to the modelled network reinforcement costs to provide an overall net investment profile for this recharging option. This overall cumulative trend in net cost with off-peak recharging option O3 is shown below, both with and without LV voltage control.

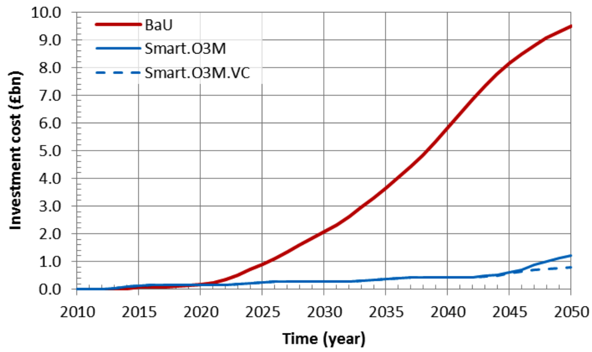


Figure 8-29 : Net Costs with Smart Off-Peak Recharging (O3). Base Case Piv Uptake. (Adapted from [31] Figure 15)

As can be seen from the figure above, the implementation of off-peak recharging during the night can potentially provide a significant net reduction in overall cost. Further, beyond 2045 additional savings are estimated when this option is implemented in conjunction with LV voltage control.

It should however be noted that the risk of not achieving a large behavioural shift to off-peak recharging is increased when a simple, 'voluntary' dual-tariff approach is taken. The implementation of such a system with an override function or a simple static tariff may not be sufficient for mitigating overloads in the distribution network and therefore for truly effective overnight recharging intelligence costs may not differ significantly from those required for locally optimised recharging (option O4).

8.3.4 Impact of Locally-Optimised Smart Recharging (O4)

The impact of fully smart recharging control is now assessed, with several different degrees of GB-wide charging available for full local optimisation considered. The remainder of recharging is assumed to occur at the end of each day, as per recharging profile O2.

The scenarios considered are:
- 25% of recharging available for locally optimised control (25% O4, 75% O2)
- 50% of recharging available for locally optimised control (50% O4, 50% O2)
- 75% of recharging available for locally optimised control (75% O4, 25% O2)
- All recharging fully optimised against local and national demand (100% O4)
- 100% fully optimised, as in iv) in addition to voltage control

Similar to before, the maximum estimated costs of enabling this recharging option in terms of the intelligence and communications infrastructure required, as described in Chapter 5, are added to the network reinforcement costs to provide an overall net investment profile. The diagram below shows the final cumulative net cost for the scenarios described above.

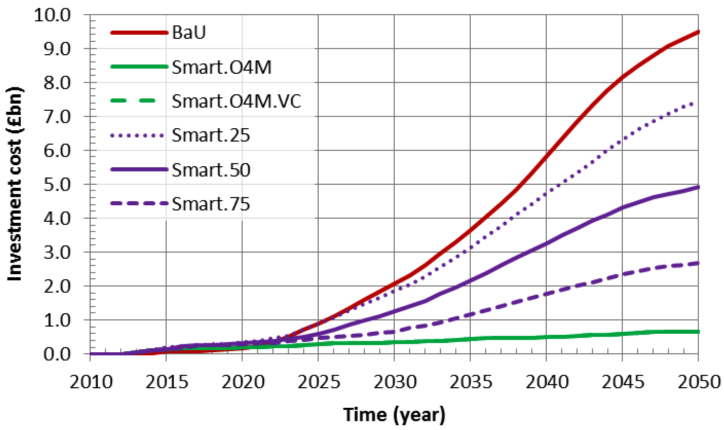


Figure 8-30 : Net Costs with Smart, Locally Optimised Recharging (O4). Base Case Piv Uptake. (Adapted From [31] Figure 15)

As expected, increasing deployment of full local optimisation of recharging can potentially provide increasing reductions in net reinforcement cost. With all recharging fully optimised (O4), cumulative reinforcement costs fall below £1bn by 2050. In this instance, the implementation of LV voltage control provides little or no additional benefit.

8.3.5 Summary of Overall Reinforcement Costs for 'Base' Uptake Case

The overall costs for the scenarios considered so far can be summarised in the diagram below using a Net Present Value (NPV) representation of the total costs over the period modelled. A discount rate of 3.5% has been used for consistency with rates used for other Government infrastructure and by the Electricity Networks Strategy Group. The overall costs are split into network reinforcement costs (labelled RC), and intelligence costs required for the implementation of smart recharging options (both least-cost specification, labelled 'IC', and maximum specification, labelled 'IC+' as described in Chapter 5).

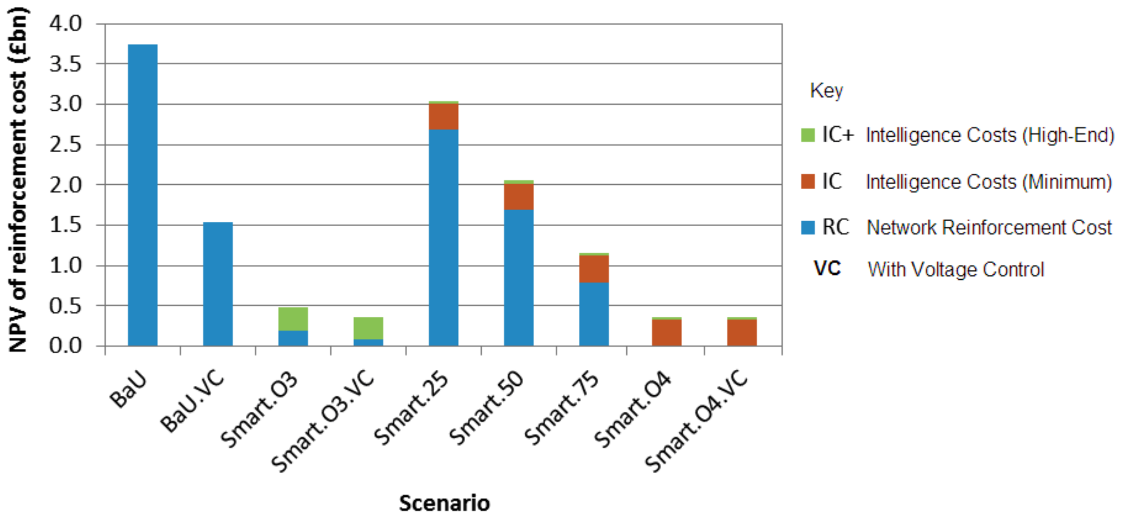


Figure 8-31 : NPV of Overall Reinforcement Costs by Scenario. Base Case Piv Uptake. ([31] Figure 16)

8.4 Assessment of Select Piv Scenarios Incorporating Impact of Electrification of the Heat Sector

The heat sector is another area identified as offering significant potential for lowering carbon emissions through the replacement of gas-fired, oil-fired and Liquefied Petroleum Gas (LPG) based domestic heating systems. The electrification of heating by way of heat-pumps is therefore expected to impose additional demands on Great Britain's distribution networks in the coming years, which is likely to drive further network reinforcement.

Given the characteristics and constraints of heat-pumps, as described further in [32], systems are likely to incorporate a level of heat storage that can be used to lower the ratings needed to meet typical heating requirements. This storage provides an opportunity to optimise heat pump operation, not only to meet local heat requirements, but also to contribute to peak minimisation of distribution network demand.

Similar scenarios have therefore been evaluated, but with additional demand included from a partial electrification of the heat sector to assess the impact on reinforcement costs. It is assumed that the penetration of heat pumps is 50% that of PiVs, with smart control available for all heat pumps and storage of 10% of daily energy requirements available.

The equivalent reinforcement costs for the BaU scenario, with heat pump demand incorporated, are shown in the diagram below for the various PiV uptake cases. As expected, the overall level of investment required is increased.

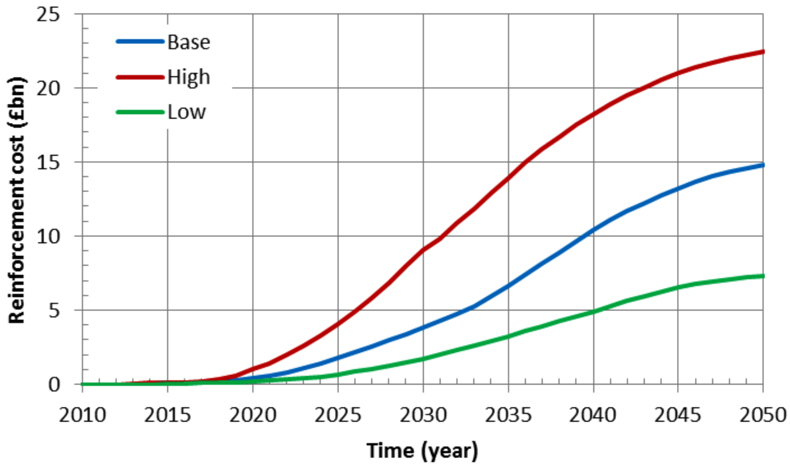


Figure 8-32 : Bau Reinforcement Costs Required for Various Piv Uptake Cases, with Heat Pump Demand. ([31] Figure 6)

With heat-pump demand incorporated, the net cost profiles when the use of voltage control and recharging applied off-peak (O3) as mitigation options are shown on the same diagram below for the 'base' PiV uptake case.

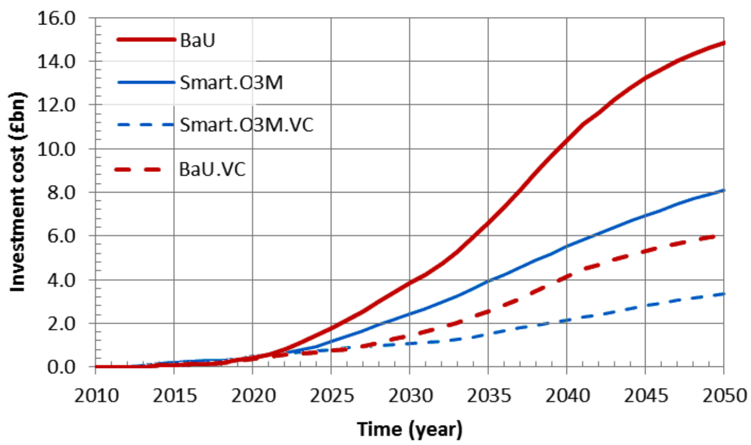


Figure 8-33 : Net Costs for Voltage Control and Smart Recharging Options (O3) with Heat-Pump Demand Incorporated. Base Case PiV Uptake. (Adapted from [31] Figure 18)

The net cost profiles for when various degrees of locally optimised smart recharging are applied (O4) as before are shown on the diagram below for the 'base' PiV uptake case.

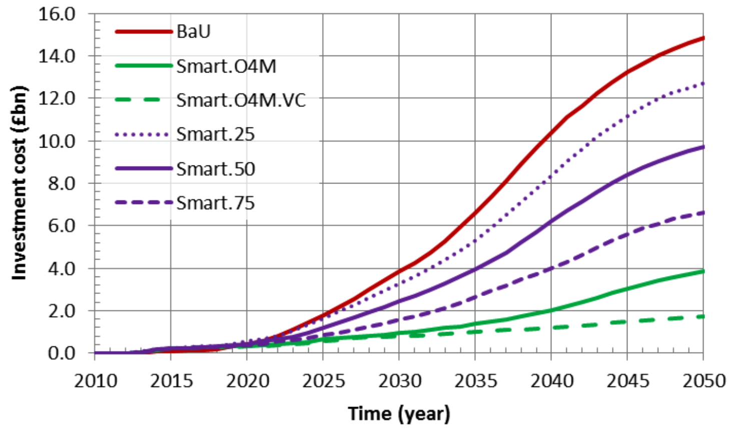


Figure 8-34 : Net Costs for Locally Optimised Recharging (O4) with Heat-Pump Demand Incorporated. Base Case Piv Uptake. (Adapted from [31] Figure 18)

As expected, it can be seen that with additional demand from the electrification of heating considered, investment is shifted forward and the overall level increased when compared to the case considering PiVs only. In the case of fully optimised recharging (O4), the implementation of LV voltage control now provides additional benefits in reducing reinforcement cost from 2035 forwards. The total reinforcement cost for BaU by 2050 is around £15bn compared with around £9.5bn considering PiVs only.

8.4.1 Summary of Overall Reinforcement Costs for 'Base' Uptake Case with Additional Demand from Heat Pumps

Similar to before, the scenarios incorporating additional demand from the electrification of heating are summarised below using NPV representations of the estimated total investments required. The costs represent the 'base' PiV uptake case and a GB-wide heat pump penetration at 50% of the overall PiV penetration.

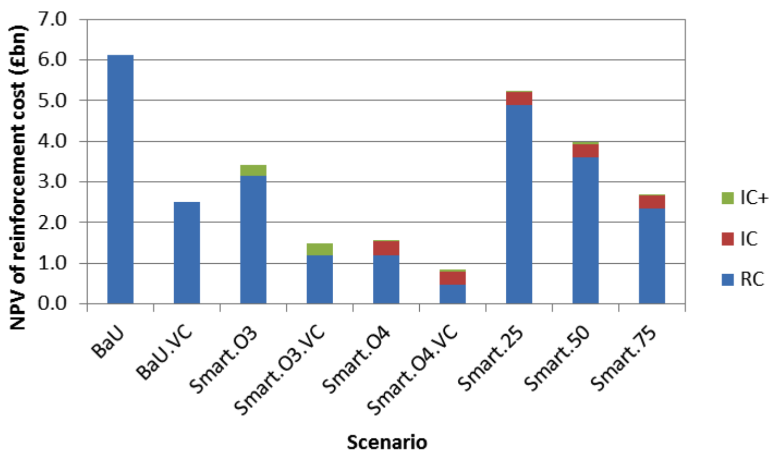


Figure 8-35 : NPV of Overall Reinforcement Costs by Scenario with Heat-Pump Demand Incorporated. Base Case Piv Uptake. ([31] Figure 19)

8.4.2 Impact of Smart Appliances

The control of smart appliances also offers opportunities to reduce peak demand in distribution networks. Considering the available reduction in daily demand from smart control of washing machines, dishwashers and tumble driers, Imperial Consultants conducted studies of the additional benefits that could be achieved on each representative network type.

It was concluded that control of smart appliances produced some limited benefits in reducing thermal overload of transformers in 'semi-rural' type networks. However for most other representative network types no significant additional benefit was observed that would not be mitigated by voltage control or locally optimised recharging (O4). This is further illustrated in the diagram below which shows no significant change to GB-wide, cumulative network reinforcement costs when locally optimised recharging (O4) with voltage control are applied, and when the control of smart appliances is also applied. The 'base' PiV uptake has been assumed, in addition to a penetration of heat pumps of 50% that of PiVs. The uptake of smart appliance control has been assumed to follow that of PiVs, with 100% penetration by 2050.

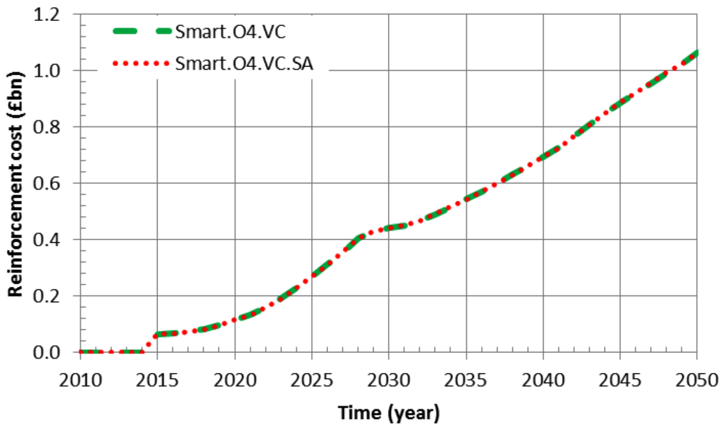


Figure 8-36 : Network Reinforcement Costs for Locally Optimised Smart Recharging with Voltage Control (O4) With and Without Smart Appliance Control. Heat-Pump Demand Incorporated, Base Case Piv Uptake [42]

8.5 Conclusions

The analyses above attempt to estimate the overall investments required in order to accommodate PiVs based on a range of mitigation scenarios including smart PiV recharging options, voltage control and the control of smart appliances. The impact of the additional demand from the electrification of heat was also considered in conjunction with these mitigation options.

A summary of the NPV of net reinforcement costs for the scenarios described above is shown in Table 8-9 and Table 8-10. The former shows the estimated NPV of costs required when only the accommodation of PiVs is considered and the latter shows the costs with the additional impact of partial electrification of the heating sector. For completeness the values for the low and high PiV uptake cases are also included in each case for comparison.

Uptake case	BaU	BaU.VC	Smart.O3	Smart.O3.VC	Smart.O4	Smart.O4.VC
Low	1.42	0.57	0.01 – 0.29	0.01 – 0.29	0.33 – 0.36	0.33 – 0.36
Base	**3.75**	**1.54**	**0.2 – 0.48**	**0.09 – 0.36**	**0.33 – 0.36**	**0.33 – 0.36**
High	7.4	3.13	3.46 – 3.74	1.44 – 1.72	0.33 – 0.36	0.33 – 0.36

Table 8-9 : Net Present Value, £Bn, for Scenarios due to Piv Recharging Only [31]

Uptake case	BaU	BaU.VC	Smart.O3	Smart.O3.VC	Smart.O4	Smart.O4.VC
Low	2.99	1.14	1.76 – 2.04	0.63 – 0.91	0.82 – 0.85	0.61 – 0.65
Base	**6.12**	**2.49**	**3.15 – 3.42**	**1.2 – 1.48**	**1.53 – 1.56**	**0.8 – 0.84**
High	10.16	4.59	5.96 – 6.24	2.55 – 2.82	3.26 – 3.29	1.59 – 1.62

Table 8-10 : Net Present Value, £Bn, for Scenarios due to Piv Recharging and Demand from Electrification of Heat-Sector [31]

Overall it can be seen that investment in intelligence to mitigate network reinforcement is the most cost-effective solution across all scenarios. In the case of low uptake of PiVs, and not considering electrification of the heat sector, it would be cost effective to deploy intelligence to facilitate recharging of PiVs off-peak in relation to the national demand profile (option O3).

For larger uptakes of PiVs, and in particular when additional demand is incorporated due to the electrification of heat, the investment in full smart functionality of intelligent infrastructure that would optimise recharging in relation to the local network loading conditions (O4) is the most cost effective option.

In addition to the investment in intelligence, deployment of in-line voltage regulators is clearly justified in case of electrification of transport and heat sectors.

9 Conclusion

Distribution network operators face a range of significant challenges in maintaining a reliable and robust energy supply as the UK transitions to a low carbon economy. New sources of generation will be more intermittent, more distributed and less controllable than before and networks will be expected to cope with power flows not conceived during original design.

In order to meet Government targets for emissions reductions, residential emissions will need to reduce significantly through a broad range of energy efficiency measures and the electrification of heating which is expected to place increased demands on the distribution networks. In conjunction with this, PiVs are expected to gain momentum as incentives and consumer confidence in the technology drives increased electrification of the transport sector placing further significant power demands on the electricity grid.

A wide-scale adoption of PiVs could cause significant challenges if existing networks are not able to accommodate the increased electrical demand due to PiV recharging, particularly if large numbers of PiVs are set to charge at the same time as the peak domestic load. Constraints arise largely from voltage drop and unbalance, violation of transformer and cable thermal limits, increases in network losses, fault levels and issues such as harmonics and step voltage changes. However, different distribution network types will have different technical characteristics as well as different levels of PiV penetrations and thus the order in which these network constraints are encountered will differ.

The amount of infrastructure reinforcement that will be required to accommodate this demand will depend on the timing, location, duration and amount of load added, which in turn will depend on a number of factors such as individual customer behaviour, electricity tariffs and PiV uptake rates. Traditional network reinforcement by way of substation upgrades and cable reinforcement is likely to be increasingly inefficient in terms of accommodating the incremental and unpredictable loads expected from PiVs and heat-pumps. Hence, if future electrical distribution networks are to realise their full potential in order to support the challenges associated with the transition to low-carbon electricity, DNOs will likely need to move away from the conventional passive reinforcement approach towards a ‘smart grid’ approach encompassing a higher degree of network operational management.

For example, using the model developed by Imperial Consultants, taking a ‘business-as-usual’ approach to accommodating a ‘base’ case moderate uptake of PiVs and heat-pumps through traditional network reinforcement is estimated to require a GB-wide investment of c£6bn (NPV) over the period 2010-2050.

Various mitigation measures can be considered to maximise, reduce or shift network utilisation to accommodate growth in demand more effectively. One such ‘network-side’ mitigation measure is voltage control on the distribution network to reduce violations in the level of voltage drop. Implementation of voltage control alone has been estimated to reduce the overall level of network reinforcement required to c£2.5bn. However experience with distributed voltage control in GB to date is relatively immature and the benefit in urban areas, where PiV uptake may be most significant, is expected to be more limited.

Implementation of 'customer-side' mitigation strategies or Demand Side Management (DSM) will play a key part in the smart grid approach. Measures such as smart control of PiV recharging, heat-pumps and micro-CHP units have the potential to mitigate significant network reinforcement costs through flattening load profiles and maximising utilisation of the network. However these solutions naturally require investment in both the intelligent infrastructure required to enable such demand response measures including communications capability, substation monitoring equipment, central control/scheduling platforms as well as costs not estimated in this report related to consumer education, engagement and awareness of such measures.

For smart control of PiV recharging, with regards to the technical infrastructure side, a range of potential development scenarios are possible depending on how metering is integrated at the consumers' recharging point. The costs of intelligent infrastructure required therefore depends to some extent on the development path taken and level of intelligence implemented; for example, for a basic dual-tariff type approach to shift PiV recharging to overnight, little investment will be required. However, smart optimisation of recharging related to local and national network conditions requires more sophisticated monitoring and control, with an estimated NPV investment of c£656m over 2010 to 2050.

With these costs of implementation included, the reduction in network reinforcement cost enabled by these demand side measures has been demonstrated to be significant. Successful control of PiV recharging overnight for example is estimated to reduce the overall GB-wide network reinforcement costs to £3.0 – £3.4bn (NPV). Fully smart, locally optimised recharging can provide further mitigation benefits and is estimated to reduce network reinforcement costs to £1.5bn (NPV).

In alignment with other research studies [28], network reinforcement and expansion costs at the LV and HV distribution level are therefore expected to be significantly greater compared to the capital expenditure and operational costs for building and maintaining the required intelligent infrastructure to enable smart PiV recharging.

For example, cost estimates provided by the Committee for Climate Change (CCC) in October 2009 [27] show that the PiV recharging infrastructure cost of accommodating 1.7 million PiVs by 2020 would be in the region of £150m – £1.5bn depending on the level of sophistication of recharging meters. According to the CCC, this would have to be funded at least in part by the UK Government. The associated LV and HV distribution network reinforcement costs for a range of PiV uptake scenarios was estimated [28] at £0.8bn – £2.6bn for the lowest-penetration scenario and between £6.2bn – £20.5bn for the highest-penetration scenario. In the same report, the benefits of employing demand response techniques were estimated with the NPV of moving towards a smarter network control paradigm was found to range between approximately £0.5bn – £1.6bn for the lowest-penetration scenario and £3bn – £10bn for the highest-penetration scenario, clearly demonstrating the need to reduce system peaks and significantly improve utilisation rates of existing generation, transmission and distribution capacity.

This report has examined the impacts of widespread uptake of PiVs on electricity distribution networks and evaluated the means by which these impacts can be mitigated. The report has also detailed the costs associated with that mitigation in terms of the different network reinforcement costs involved and the costs of building the intelligent infrastructure to optimise recharging of PiVs.

10 Glossary of Terms

ABSD – Air Break Switch Disconnectors
AC – Alternating Current
ACB – Air Circuit Breakers
AMI – Advanced Metering Infrastructure
BaU – Business As Usual
CCGT – Combined Cycle Gas Turbine
CCS – Carbon Capture and Storage
CDU – Customer Display Unit
CHP – Combined Heat and Power
CI – Customer Interruption
CML – Customer Minutes Lost
CPP – Critical Peak Pricing
DCC – Data Communications Company
DECC – Department of Energy and Climate Change
DE7 – Domestic Economy 7
DG – Distributed Generation
DNO – Distribution Network Operator
DUoS – Distribution Use of System
DSM – Demand Side Management
ESM – Energy Storage Management
ENA – Energy Networks Association
ENSG – Electricity Networks Strategy Group
EV – Electric Vehicle
FAN – Field Area Networks
FPI – Fault Passage Indicators
GDP – Gross Domestic Product
GEMA – Gas and Electricity Market Authority
GSP – Grid Supply Point
HP – Heat Pump
HV – High Voltage
Hz – Hertz – Unit of measurement for frequency
I/C – Interruptible/Curtailable
IED – Intelligent Electronic Devices
IFI – Innovation Funding Incentive
ISO – International Standards Organisation
IT – Information Technology
kVA – Kilo Volt Amperes
kV – Kilovolts
kW – Kilowatts
LAN – Local Area Networks
LCNF – Low Carbon Networks Fund
LPG – Liquefied Petroleum Gas
LV – Low Voltage
MVA – Mega Volt Amperes
MV – Megavolts
NOx – Oxides of Nitrogen
NOP – Normal Open Points
NPV – Net Present Value
Ofgem – Office of Gas and Electricity Markets
OLTC – Online Tap-Changers
PHEV – Plugged-in Hybrid Electric Vehicle

PiV – Plugged-in Electric Vehicle
RCD – Residual Current Device
R&D – Research and Development
RIIO – Revenue = Incentives + Innovation + Outputs
RMU – Ring Mains Units
RPR – Reverse Power Relay
RTP – Real-time Pricing
SCADA – Supervisory Control and Data Acquisition
SoC – State of Charge
SOx – Sulphur Dioxide
SSEG – Small Scale Embedded Generation
SSN – Substation Node
T&D – Transmission and Distribution
THD – Total Harmonic Distortion
ToU – Time of Use
TV – Television
V2G – Vehicle to Grid
V2H – Vehicle to Home
VUF – Voltage Unbalance Factor
WAN – Wide Area Networks

11 References

[1] HM Government, 'The UK Low Carbon Transition Plan – National Strategy for Climate and Energy', July 2009.
[2] HM Government, 'The UK Low Carbon Transition Plan – National Strategy for Climate and Energy', July 2009
[3] Department of Energy and Climate Change, 'Energy Metering – A Consultation on Smart Metering for Electricity and Gas', May 2009
[4] Department of Energy and Climate Change, 'Smart Metering Implementation Programme – Prospectus', July 2010
[5] Department of Energy and Climate Change, 'Smart Metering Implementation Programme – Statement of Design Requirements', July 2010
[6] Department of Energy and Climate Change, 'Smarter Grids: The opportunity', December 2009
[7] HM Government, 'The UK Renewable Energy Strategy', July 2009
[8] Ofgem, 'Regulating energy networks for the future: RPI-X@20 recommendations – Consultation', July 2010
[9] Ofgem, 'Low Carbon Networks Fund', Available at: http://www.ofgem.gov.uk/Networks/ElecDist/lcnf/Pages/lcnf.aspx
[10] Ofgem, 'RIIO: a new way to regulate energy networks – Final Decision', October 2010
[11] Electricity Networks Strategy Group, Smart Grid Working Group, 'A Smart Grid Vision', November 2009.
[12] Electricity Networks Strategy Group, Smart Grid Working Group, 'A Smart Grid Route Map, February 2010
[13] Strbac G. et al, 'Benefits of advanced smart metering for demand response based control of distribution networks', April 2010
[14] SAE International Hybrid Task Force, 'Standard J2847/1: Communication between Plug-in Vehicles and the Utility Grid', April 2010
[15] Energy Networks Association, 'Engineering Recommendation P2/6: Security of supply', July 2006
[16] The Distribution Code and the Guide to the Distribution Code of Licensed Distribution Network Operators of Great Britain: Issue 12: February 2010. Available at: http://www.energynetworks.info/dcode-homepage
[17] Energy Networks Association, 'Engineering Recommendation P29: Planning limits for voltage unbalance in the United Kingdom for 132 kV and below', March 1990
[18] Seppo Kärkkäinen. 'Integration of Demand Side Management, Distributed Generation, Renewable Energy Sources and Energy Storages', Available at: http://www.ieadsm.org/Files/Exco%20File%20Library/Key%20Publications/Synthesis Finalvol1.pdf
[19] Energy Networks Association, 'Engineering Recommendation G74: Procedure to meet the requirements of IEC 909 for the calculation of short-circuit currents in three-phase AC power systems', 1992
[20] Yang, C., McArthy. R.W. 'Electricity grid: Impacts of plug-in electric vehicle charging.' Environmental Management 2009, p. 16-20
[21] Staats, P.T., Grady, W.M., Arapostathis, A., Thallam, R.S. 'A statistical method for predicting the net harmonic currents generated by a concentration of electric vehicle battery chargers', IEEE Trans. on Power Delivery, 12 (3), p. 1258 – 1266, July 1997
[22] Energy Networks Association, 'Engineering Recommendation G5/4: Planning levels for harmonic voltage distortion and the connection of non-linear equipment to transmission and distribution networks in the United Kingdom', 2001

[23] Electricity Association., 'Engineering Recommendation P28: Planning limits for voltage fluctuations caused by industrial, commercial and domestic equipment in the United Kingdom', 1989
[24] Hadley, S.W. 'Impact of plug-in hybrid vehicles on the electric grid', Oak Ridge National Laboratory, October 2006
[25] WP1.1-2, Derived PIV uptake rates and sales volume forecasts
[26] Cenex and Arup, 'Investigation into the scope for the transport sector to switch to electric vehicles and plug-in hybrid vehicles', Department for Business Enterprise and Regulatory Reform: Department for Transport, October 2008
[27] Committee on Climate Change, Electric cars. Available at: http://www.theccc.org.uk/sectors/transport/electric-cars
[28] Centre for Sustainable Electricity and Distributed Generation Imperial College, ENA, Benefits of Advanced Smart Metering for Demand Response based Control of Distribution Networks, April 2010
[29] SP2/IMP/17, Strbac G. et al, Evaluating the Impact of Plug-in Vehicles on GB Electricity Distribution Networks
[30] SP2/IMP/09, Strbac G. et al, Potential Reinforcement/Mitigation Options
[31] SP2/IMP/14, Strbac G. et al, Mitigation Strategy Cost Estimation
[32] SP2/IMP/16, Strbac G. et al, Potential Benefit/Impact of Distributed Energy Sources and Demand Side Management Evaluation
[33] SP2/IBM/28, Baker-Brian et al, Intelligent Infrastructure Delivery – Phases, Options, Costs and Risks, Dec 2010
[34] SP2/IBM/16, Baker-Brian et al, Conceptual Business Architecture
[35] Ravens, S., Optimising customer engagement in smart meter deployments, Feb 2011
[36] SmartGridCity Project, Boulder, US. www.smartgridnews.com
[37] SP2/IMP/01, Strbac G. et al,
[38] SP2/IMP/03, Strbac G. et al, Final List of Generic Networks, August 2010
[39] SP2/IMP/04, Strbac G. et al, Set of Generic Networks for GB wide analysis of Distribution Systems, August 2010
[40] SP2/EDF/05, Pelletier A, Evaluate the costs associated with electricity distribution network 'intelligence' upgrades that may be required, March 2011
[41] SP2/IMP/18, Strbac G. et al, Macro-Level Model Beta Version
[42] Djapic P, Impact of Smart Appliance Control Charts