

Benefits of Advanced Smart Metering for Demand Response based Control of Distribution Networks

Summary Report

Version 2.0

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1 Executive summary

- 1.1 This study is conducted in collaboration with the Energy Networks Association to inform the current debate on the smart metering roll out programme in relation to the appropriate functionality of smart meters and corresponding requirements on communication infrastructure. The overall aim of the investigation is to estimate the order of magnitude benefits of future real-time distribution network control that incorporates real time demand response facilitated by smart metering infrastructure. Although the scope of the benefits evaluated is limited to distribution networks and excludes substantial benefits that may be associated with transmission and generation infrastructure, this analysis should contribute to establishing a business case for advanced metering functionality.
- 1.2 This work is conducted in the context of the challenges associated with the future GB electricity system. By 2020, according to the Government Renewable Energy Strategy, it is expected that 35% of the UK electricity demand will be met by renewable generation (an order of magnitude increase from the present levels). In the context of the targets proposed by the UK Government Committee on Climate Change (greenhouse gas emission reductions of at least 80 percent in 2050) it is expected that the electricity sector would be almost entirely decarbonised by 2030, with potentially significantly increased levels of electricity production and demand driven by the incorporation of heat and transport sectors into the electricity system. One of the key concerns with the future GB low carbon electricity system is that it may be characterised by much lower generation and network asset utilisations given (i) a significant penetration of low capacity value wind generation combined with (ii) a potential increase in peak demand that is disproportionately higher than the increase in energy, which may be driven by the incorporation of the heat and transport sectors into electricity. However the transport and heat sectors are characterised by significant inherent storage capabilities and this opens up unprecedented opportunities for utilising demand side response, not only to optimise electricity production capacity but also to enhance the efficient provision of network capacity.
- 1.3 Delivering the carbon reduction targets cost-effectively, through demand side response optimisation, will require a fundamental shift from a passive to an active philosophy of network control. This shift, enabled by the incorporation of demand response into system operation and design, can be facilitated by the application of a smart metering system supported by an appropriate information, communication and control infrastructure. In this work a number of possible future development scenarios over the next 20 years have been analysed. This is related to different rates of uptake of electric vehicles and heat pumps in the period under consideration. In choosing development scenarios we have not attempted to predict the most likely future developments; rather we have investigated the boundaries of possible outcomes over a full range of scenarios. Furthermore, we have also conducted a spectrum of sensitivity studies to investigate the potential impact of a number of key influencing factors.
- 1.4 Our analysis demonstrates that optimising responsive demand has the potential to reduce the system peak and the need for system reinforcement by a very considerable amount. At the national level, full penetration of Electric Vehicles (EVs) and Heat Pumps (HPs) could increase

the present daily electricity consumption by about 50%, while doubling the system peak (requiring in turn significant generation and network reinforcements). However, by optimising demand response the peak increase could be restricted to only 29%, resulting in massively improved utilisation of generation and network capacity, and significantly reduced network investment. At the local distribution network level, which is the focus of this study, significant benefits of optimising demand response in relation to the network capacity are observed even for very low levels of penetration of electric vehicles and heat pumps.

1.5 Given that future costs of distribution network reinforcement will be driven by the network control paradigm, this work contrasts two approaches:

- First, following the present ‘unconstrained’ network operation philosophy with the distribution network control problem being resolved in the planning stage, i.e. the “Business as Usual (BaU)” approach where the distribution network is designed to accommodate any reasonably expected demand; and
- Second, involving real time network management¹ through optimising demand response, i.e. a paradigm shift in network control philosophy that uses the advanced functionality of smart meters and an appropriate communication infrastructure, i.e. the “Smart” approach to optimise responsive demand at the local level in order to manage network constraints and avoid or postpone network reinforcements. In this case, demand response will be time and location specific.

1.6 Several representative distribution networks have been created and analysed to predict the network reinforcement cost (at the GB level) associated with the two network control philosophies across several future development scenarios with different levels of penetration of EVs and HPs as shown in Figure 1-1.

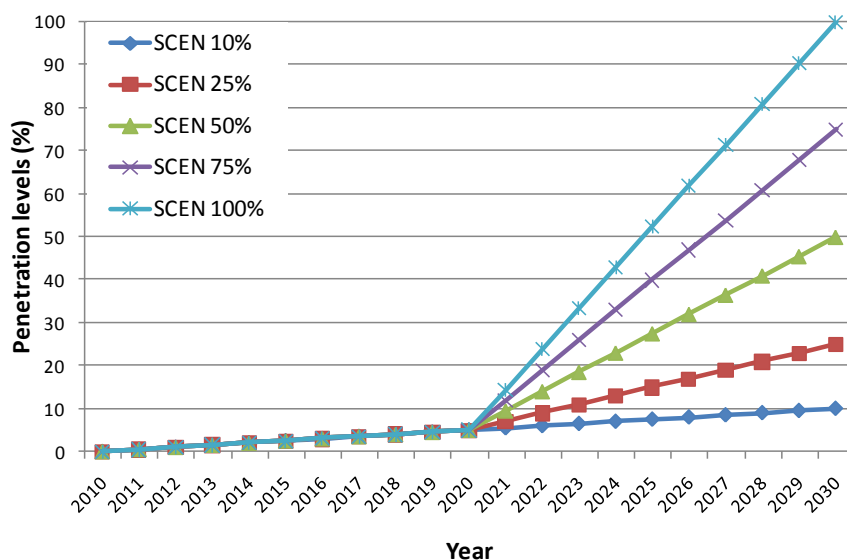


Figure 1-1: Penetration scenarios considered

¹ Given the context of management of power flow and voltage profiles in distribution networks, an appropriate latency (time scale) for Real Time Control would be in the order of several minutes.

- 1.7 This is consistent with the government-projected cumulative penetration of 1.7 million cars by 2020 (approximately 5% penetration). From 2020 to 2030, 5 different levels of uptakes of EVs and HPs are considered, from a scenario with a very slow uptake of EVs and HPs (SCEN 10%), to a scenario with high EV and HP growth rates in which a full penetration is achieved by 2030 (SCEN 100%). The Impact on distribution network investment requirements is then assessed for these scenarios and corresponding Net Present Value (NPV) of network reinforcement costs evaluated. We considered alternative network reinforcement strategies to determine likely minimum and maximum NPV reinforcement costs associated with the two network operation approaches, as shown in Table 1-1. However, the benefits identified are conservative as the optimisation of EV charging and HP operation is carried out to minimise the aggregate peak load rather than constraint violations at the individual LV feeder sections.
- 1.8 The results show that the passive, unconstrained network operation approach (BaU) will require a significantly higher proportion of the distribution network to be reinforced when compared with an active real time control approach (Smart).
- 1.9 As shown in Table 1-1, the total network reinforcement costs are dominated by the low voltage networks. Furthermore, we observe that reinforcements in urban areas are primarily driven by thermal overloads, while for semi-urban/rural and rural networks this is mostly due to excessive voltage drops (indicating that, in future, the value of alternative voltage control strategies may be significant).

Table 1-1: GB NPV of network reinforcement costs for two network control approaches and the associated value of smart meter-enabled active control

Scenarios	NPV costs LV (£bn)		NPV costs HV (£bn)		NPV Value of Smart (£bn)
	BaU	Smart	BaU	Smart	
SCEN 10%	0.75 - 2.48	0.30 - 0.98	0.06 - 0.20	0.03 - 0.08	0.48 - 1.62
SCEN 25%	1.90 - 6.26	0.70 - 2.32	0.20 - 0.66	0.04 - 0.13	1.36 - 4.47
SCEN 50%	3.76 - 12.4	1.48 - 4.88	0.30 - 1.00	0.13 - 0.42	2.45 - 8.10
SCEN 75%	5.08 - 16.72	2.47 - 8.12	0.34 - 1.11	0.22 - 0.71	2.73 - 9.00
SCEN 100%	5.85 - 19.27	2.91 - 9.59	0.37 - 1.21	0.26 - 0.85	3.05 - 10.04

- 1.10 By comparing the NPV cost of BaU and Smart, the NPV value of an active distribution grid facilitated through real time demand response is estimated. We observe that the benefits of advanced metering functionality are proportionally greater for smaller penetration scenarios. For high penetration levels the benefits of optimising demand response saturate, given rise to the need to reinforce the network to accommodate increases in network loading driven by very high levels of EVs and HPs.
- 1.11 We note that the Net Present Value of changing the network control paradigm ranges approximately between £0.5bn and £10bn, across all scenarios considered. This difference in the network reinforcement cost between the two approaches in effect defines (a part of) the

budget (available today) for changing the network control paradigm². This is relevant as such a change would be accompanied with investment in advanced smart meter functionality; in the communication infrastructure needed to support real time network control; and possibly in the enhancement of information and management systems associated with the new control paradigm. In this context, this work enables the benefits of the new network control paradigm to be quantified and hence inform the development of a business case for advanced metering functionality.

- 1.12 It is important to emphasise that this analysis is based on diversified household load profiles and (historical) average national driving patterns applied to all local networks. However significant deviations would be expected in individual circumstances and it has, for example, been shown that the impact of specific driving patterns may be very significant. Furthermore, these load patterns would vary significantly in magnitude, location and across time, which could have very considerable effects on the load and voltage profile of local LV networks in particular. Recognising the specific conditions on individual LV feeder sections, driven by actual behaviour of time-varying loads in specific locations, will be critical for enhancing the utilisation of the existing assets and avoiding network reinforcements. Given that this analysis is based on fixed, average load patterns, and it does not capture the variability of particularly lumpy loads, the benefits of active network control are underestimated. In addition, the application of hourly time resolution and assuming fully balanced loading conditions in LV networks will also result in the benefits being undervalued.
- 1.13 On the other hand, there will be a spectrum of other potentially significant benefits of advanced smart metering functionality and enhanced communication infrastructure that have not been considered in this study, but are recommended for further investigation. These include: benefits from reduced generation capacity requirements; provision of flexibility and contribution to national and regional system balancing and enhanced utilisation of the transmission network; improved outage management and better investment optimisation; and greater capacity to accommodate low-carbon generation and load growth. Moreover, the ability to influence responsive demand in real time through smart meters will have the potential to increase the ability of the system to accommodate a range of future energy scenarios; incorporate vehicle-to-grid applications; and enable DNOs to contribute to the national demand-supply residual balancing function and improve real-time management of the GB transmission system. Some of these benefits are currently being investigated in more detail.
- 1.14 This work does not consider distribution network asset replacements that may need to be carried out due to aging of equipment, as major renewals of HV and LV underground cable infrastructure due to condition degradation over the period to 2030 are not currently envisaged. Furthermore, the increase in network utilisation, which would be achieved through an active control philosophy, would lead to an increase in distribution network losses, particularly for higher levels of penetration of EVs and HPs. However, the estimated NPV of the increased losses over the period under consideration is demonstrated not to be material.

²We have also conducted a number of sensitivity studies to test the robustness of our conclusions. For example, in case of a very low uptake of electric vehicles by 2030 of 10% and no uptake of heat pumps, the NPV benefits of changing network operation philosophy would be still significant, approximately in the range between £0.25bn and £1bn.

Moreover, the potentially significant impact of a large-scale penetration of small sized distributed generation together with more efficient use of energy have the potential to release network capacity that could be used to accommodate some of the increase in demand. These effects will be explored in future studies. Finally, the optimisation of heat pump operation is achieved through incorporating a modest level of storage designed to deliver system benefits, although establishing the economics of alternative storage options will need further investigation.

- 1.15 Clearly, very significant opportunities for optimising demand response in relation to network loading have been identified and quantified. It is very important however to appreciate that the optimal demand response will be highly time and location-specific. Theoretically, an optimal time scheduling of individual household loads, specific to each individual location, could be determined for pre-specified user requirements. Assuming that these requirements at each individual location are fixed in time (fixed EV charging requirements and pattern, fixed Smart Appliances and heat pump operating patterns), such an objective of optimal scheduling could be hypothetically achieved through a location-specific (at the household level) time of use tariff. However, all these loads will, frequently and very significantly, deviate from any pre-specified schedule. Demand response will therefore need to be re-optimised for the actual situation arising, otherwise such deviations will potentially lead to LV network overloads and/or voltage profiles breaching statutory limits, given the lack of diversity and 'lumpiness' of loads associated with electric vehicles and heat pumps. The instantaneous increase in load caused by the simultaneous charging of an electric vehicle and operation of a heat pump (for example on returning home) can be in excess of 10kW per household which is indeed very significant. Only real time demand response optimisation, specific to changing user requirements and network constraints, can fully deliver the potential savings from enhanced asset utilisation and reduced network reinforcement. This in turn requires advanced smart metering functionality accompanied with appropriate communication infrastructure in order to allow real time optimisation of demand response.
- 1.16 Real time network control that incorporates demand response will also have significant implications on the UK regulatory and commercial arrangements, as maintaining the present structure where supply and network businesses act independently will lead to inefficient network investment. Establishment of a Distribution System Operator type function, together with appropriate distribution network access and energy pricing structures, may need to be developed to facilitate both efficient real time network operation and efficient investment in future network reinforcements (conceptually, maximising real time optimisation of responsive demand could be achieved through a real time pricing scheme).
- 1.17 Notwithstanding the further opportunities identified for more refined analyses, the analyses undertaken as part of this study have clearly illustrated (and quantified) the benefits to customers (ultimately reflected in terms of avoided electricity charges) of adopting an active network control approach based on optimised demand side response enabled by smart metering functionality and an enhanced communication infrastructure. Moreover this report has clearly illustrated that, even at relatively low EV and HP penetration levels, there are significant benefits of a Smart control paradigm over a BaU 'unconstrained' paradigm. It therefore follows that the benefits of a Smart approach will be significantly front-loaded under any ultimate EV and HP penetration scenario. In particular it points to a need to adopt

a Smart approach from the outset and hence in the context of the proposed GB Smart Meter Implementation Programme, a compelling case to develop a smart metering and communications functional specification that will enable the required paradigm to be realised. It is worth mentioning that overseas smart metering programmes, to the best of our knowledge, will be designed to facilitate real time demand response and the required paradigm change in distribution network operation.

2 Background, objective and scope of work

- 2.1 The UK electricity system faces challenges of unprecedented proportions. By 2020, according to the Government Renewable Energy Strategy (RES), it is expected that up to 35% of the UK electricity demand will be met by renewable generation (an order of magnitude increase from the present levels). In the context of the targets proposed by the UK Government Committee on Climate Change (greenhouse gas emission reductions of at least 80 percent in 2050) it is expected that the electricity sector would be almost entirely decarbonised by 2030, with potentially significantly increased levels of electricity production and demand driven by the incorporation of heat and transport sectors into the electricity system.
- 2.2 Given the significant penetration of low capacity value wind generation, combined with a potential increase in peak demand that is disproportionately higher than the increase in energy, driven by the incorporation of the heat and transport sectors, the future electricity system could be characterised by much lower generation and network asset utilisation (in other words very costly provision, and inefficient use, of capacity). Delivering these carbon reduction targets cost-effectively will need higher asset utilisation levels to be achieved which could be delivered through a fundamental shift from a passive to an active philosophy of network operation. This shift can be enabled by the incorporation of demand into system operation and design, facilitated by the application of smart metering supported by an appropriate information, communication and control infrastructure.
- 2.3 In this context, this study has been conducted in collaboration with the UK Energy Networks Association to inform the current GB smart metering implementation programme in terms of the appropriate functionality to be incorporated within the smart meters and the corresponding requirements on the associated communication infrastructure. The overall objective of the investigations carried out is to assess the potential benefits of integrating smart meters, with appropriate functionality and communication systems, into real-time distribution network control. This is aimed at reducing the need for network reinforcement through optimising, at the local level, demand response of smart electric appliances and electrified transport and heat sectors. Although the scope of the benefits evaluated is limited to distribution networks and excludes substantial benefits that may be associated with transmission and generation infrastructure, this analysis should contribute to establishing a business case for advanced metering functionality.
- 2.4 Future costs of network reinforcement will be driven by the network control and design concepts and hence this work contrasts two approaches:
 - First, following the present 'unconstrained' network operation philosophy with the distribution network control problem being resolved in the planning stage, i.e. Business as Usual (BaU) approach where the distribution network is designed to accommodate any reasonably expected demand; and
 - Second, involving real time network management through optimising demand response, i.e. a paradigm shift in network control philosophy that uses the advanced functionality of smart meters and appropriate communication infrastructure, i.e. the Smart approach to

- optimise responsive demand at the local level in order to manage network constraints and avoid or postpone network reinforcements.
- 2.5 Under the operation paradigm 'Smart', that optimises demand response in real time to minimise the impact on the network, constraints associated with demand flexibility are respected, so that the intended service quality is not affected (i.e. vehicles are charged so that every intended journey can be carried out; it does not lead to any additional constraints on EV usage).
 - 2.6 The scenarios analysed in this study are related to different rates of uptake of electric vehicles and heat pumps over the next 20 years. In choosing scenarios we have not attempted to predict future developments; rather we have investigated the boundaries of possible outcomes over a full range of scenarios. Furthermore, we have also conducted a spectrum of sensitivity studies to investigate the potential impact of a number of key influencing factors.
 - 2.7 This study quantifies the costs (and the corresponding Net Present Value) of distribution network reinforcements associated with these two network control philosophies, i.e. without active demand side participation (Business as Usual) and with optimised demand response (Smart). The difference in the NPV of network reinforcement costs between the two approaches will in effect define (part of) the budget for changing the network control paradigm.
 - 2.8 The analysis carried out in this investigation focuses on Low Voltage (LV) and High Voltage (HV) distribution networks, given that these assets dominate the overall distribution network costs. Furthermore, the inclusion of Extra High Voltage (EHV) networks would require more accurate modelling of demand diversity which could not be accomplished within this study. This implies that the results obtain are somewhat conservative as the benefits of demand response on Extra High Voltage networks are not considered.
 - 2.9 In terms of the modelling approach adopted in this study, hourly time resolution was adopted due to data availability although shorter time intervals would be desirable particularly for consideration of loads and voltages on LV feeders given the potential lack of diversity and 'lumpiness' of load associated with electric vehicles and heat pumps. Furthermore, while average daily driving patterns of electric vehicles have been considered, in practice, driving behaviour can vary from the average, both in location and time. Sensitive studies carried out suggest that the benefits presented by this analysis may as a consequence be conservative. Moreover, to model heat pump operation, only a limited number of sample dwelling types have been used, and it is likely that the analysis would benefit from expanding the number of heat pump samples and designs. Finally, only a limited number of representative networks have been considered and in particular circumstances network topology and parameters may deviate from these. These highlighted issues, albeit not sufficient to fundamentally change the conclusions of this report, will nevertheless be used to steer future efforts towards further enhancing the analysis in this report.
 - 2.10 It is important also to note that there is a variety of other important benefits of advanced smart metering functionality and enhanced communication infrastructure that have not been considered in this study, but are recommended for further investigations. These include: improved outage management; better investment optimisation; and greater capacity to

accommodate low-carbon generation. Moreover, the ability to influence responsive demand in real time through smart meters will have the potential to increase the ability of the system to accommodate a range of future energy scenarios; incorporate vehicle-to-grid applications; and enable DNOs to contribute to the national demand-supply residual balancing function and improve real-time management of the GB transmission system. On the other hand this work does not consider distribution network asset replacements that would need to be carried due to aging of equipment, which could represent an opportunity to carry out a strategic asset replacement of higher capacity in anticipation of higher network loading³ (this would potentially reduce the benefits of active distribution management facilitated by an appropriate smart metering functionality).

³ Note however that major renewals of HV and LV underground cable infrastructure due to condition degradation over the period to 2030 are not currently envisaged

3 Demand modelling

3.1 This section focuses on describing the categories of flexible demand that were included in the analysis of the role of responsive demand in improving the efficiency of system operation and planning. Three categories of demand technologies are considered here: electric vehicles (EVs), heat pumps (HPs) and smart domestic appliances (SAs). There are other types of controllable demand that could be used for the same purpose as the ones mentioned above. However, due to data availability, operational flexibility, and perceived importance in terms of future electricity system decarbonisation targets, it is well understood that these three categories could have the most profound impact future distribution network operation and design.

Modelling of demand of electric vehicles

- 3.2 Electric vehicles are widely seen as one of the key policy instruments to enable shifting of transport demand from fossil fuels to the electricity sector that relies on renewable and low-carbon electricity generators.
- 3.3 For the purpose of this study, a detailed National Transport Survey⁴ (NTS) database is used. Data extracted from the NTS database contains detailed information on all journeys conducted by light vehicles including starts and ends of individual journeys grouped according to distances travelled. The NTS data is classified into 12 distance bands (e.g. less than 1 mile, 1 to 2 miles, 2 to 3 miles etc.). A small sample of the data set is presented in Table 3-1⁵.

Table 3-1: Driving patterns data

Start time	End time	Distance band	No. of journeys (daily)
00:00 – 00:59	00:00 – 00:59	Under 1 mile	6922
00:00 – 00:59	00:00 – 00:59	1 to under 2 miles	15987
00:00 – 00:59	00:00 – 00:59	2 to under 3 miles	14848
...
00:00 – 00:59	01:00 – 01:59	2 to under 3 miles	1277
00:00 – 00:59	01:00 – 01:59	3 to under 5 miles	4938
00:00 – 00:59	01:00 – 01:59	5 to under 10 miles	3209
...
00:00 – 00:59	02:00 – 02:59	50 to under 100 miles	474
00:00 – 00:59	03:00 – 03:59	100 to under 200 miles	492
00:00 – 00:59	04:00 – 04:59	200 miles and over	388
...
23:00 – 23:59	23:00 – 23:59	25 to under 35 miles	7750
23:00 – 23:59	23:00 – 23:59	35 to under 50 miles	1458
23:00 – 23:59	23:00 – 23:59	50 to under 100 miles	923

⁴ National Travel Survey Database 2008, Department for Transport, UK, 2009, <http://www.dft.gov.uk/>.

⁵ For more detailed analysis, on-board consumption, particularly air conditioning load, for both cooling and heating, may need to be added.

- 3.4 On the basis of the records, approximately 67.4 million journeys are undertaken daily on average, by around 34.2 million vehicles [11] (i.e. on average, each car undertakes approximately 2 journeys per day). Average daily distance travelled by all vehicles is approximately 1 billion kilometres, which equates to slightly less than 30 kilometres per vehicle. Based on the literature available on EVs, an average energy consumption of 0.15 kWh/km⁶ is used in this work. Assuming that the entire population of light/medium size vehicles is converted to electricity, the total daily energy requirement would amount to around 150 GWh, or about 4.4 kWh per vehicle.
- 3.5 Based on the NTS data, each pattern of journeys is characterised by the number of vehicles involved along with start and end times of each journey, as well as the energy needed for each journey. The database created for the assessment undertaken in this study contains approximately 44,000 combinations of journeys. Long journeys (above 100 miles) have been excluded from the analysis since they are unlikely to be feasible without recharging (although relatively few vehicles regularly undertake such journeys, their overall impact is estimated to be small).
- 3.6 On the basis of data prepared in this fashion, with an average of approximately two journeys carried out by each car, simulation / optimisation of alternative charging strategies can be modelled, given that the energy consumed during the journey is specified together with the times when vehicles are stationary and with an opportunity to be connected to the electricity system. Our simulation / optimisation algorithms would ensure that the state of charge of batteries would not compromise the ability of vehicles to carry out their intended journeys.
- 3.7 Based on the available literature, in this exercise the central case model adopts 6kW as the maximum power for charging EV batteries. However sensitivity analysis has been undertaken to test the impact of 3.3 kW and 12 kW charging demands (note: this does not cover 'rapid' charging applications).
- 3.8 EV loads are particularly well placed to support network operation: given their relatively modest amount of energy required; the short driving times generally associated with small passenger vehicles (vehicles are stationary on average for 90% of the time); and given that the batteries have relatively high power ratings. Clearly, there is considerable flexibility regarding the time when the vehicles can be charged (providing the availability of charging infrastructure) and this can provide significant benefits both to the operation of distribution and transmission networks and to the efficient dispatch and utilisation of generation. In this work we have not explicitly considered vehicle-to-grid applications (discharging car batteries to support the grid⁷).

Modelling of Domestic Electric Heat Pumps

- 3.9 The heat sector is another area that has significant potential for decarbonising, both through replacing older gas-fired, and especially oil-fired or LPG-based (more than 8.2% of domestic space and water heating is based oil or solid fuel), domestic heating with electricity-based

⁶ Values between 0.11 kWh/km and 0.2 kWh/km are reported in literature [10], [12]

⁷ By excluding explicit assessment of V2G concepts (which is still a controversial topic), our analysis provides conservative estimates regarding the benefits of incorporating EV demand response for real time network control facilitated by advanced smart metering functionality and corresponding communication network.

heating provided by electric heat pumps (HP)⁸ and using heat pumps as a low carbon space heating option for new housing (including for example in the construction of ‘Zero Carbon Homes’ from 2016). This concept relies on the assumption that future electricity systems will be largely carbon-neutral as a result of adopting renewable, nuclear and other low-carbon generation technologies.

- 3.10 A heat pump can be either an air-source or closed-loop ground-source type. The key parameter of the heat pump performance is its Coefficient of Performance (COP). When the heat pump is used for heating, COP is defined as the ratio of the heat supplied to the energy carrier medium, to the electric input into the compressor. Although ground source heat pumps generally provide better energy performance (as the ground or underground water provides a more stable temperature source than air) installation costs are higher and this potentially represents a barrier to wide application (notwithstanding anticipated fiscal support arising from the Renewable Heat Incentive).
- 3.11 The UK residential heating market consists of approximately 26 million dwellings, with annual thermal demands typically in the range 10,000-30,000 kWh (thermal) that corresponds to the thermal energy required for space heating and domestic hot water needs. The data associated with the operation of heat pumps used in this work is derived from empirical studies and field trials of micro-CHP and boiler systems conducted by the Carbon Trust⁹.
- 3.12 In Figure 3-1 below, an electricity demand profile of an individual heat pump, mimicking the operation of a boiler or a micro CHP, is presented (the corresponding distribution of ratings of the heat pumps is presented in Table 3-2). The Figure also presents aggregate demand of the operation of 21 HPs with hourly time resolution. A single dwelling heat pump profile represents a typical operation pattern with distinct on and off operation of the heating system with time-driven control. In this work we assumed improvements in energy efficiency, and the analysis is carried out under the assumption of achieving Grade A insulation levels in dwellings heated by HPs.

Table 3-2: Distribution of ratings of Heat Pumps ratings

	HP rating (kW)		
Ranges (kW)	2 – 3	3 – 4	4– 6
%	14%	76%	10%

The analysis is carried out under the assumption of achieving Grade A insulation levels in dwellings heated by HPs. The heat demand of an average UK dwelling under the cold weather conditions is evaluated in order to assess the impact of heat pumps on the electricity system. Under a full penetration of heat, the additional electrical load could reach about 45 GW which could coincide with the existing system peak. In terms of energy consumption, the aggregate

⁸ There are other approaches for decarbonising the heat sector, for example using community heating schemes supplied from waste heat produced by fossil fuel plant. Although such approaches are not considered in this exercise, this study could inform comparisons of alternative options.

⁹ Carbon Trust, Micro-CHP accelerator interim report, 2007.

daily demand of all heat pumps for a cold winter day would be around 460 GWh, representing more than 40% of the existing winter daily demand.

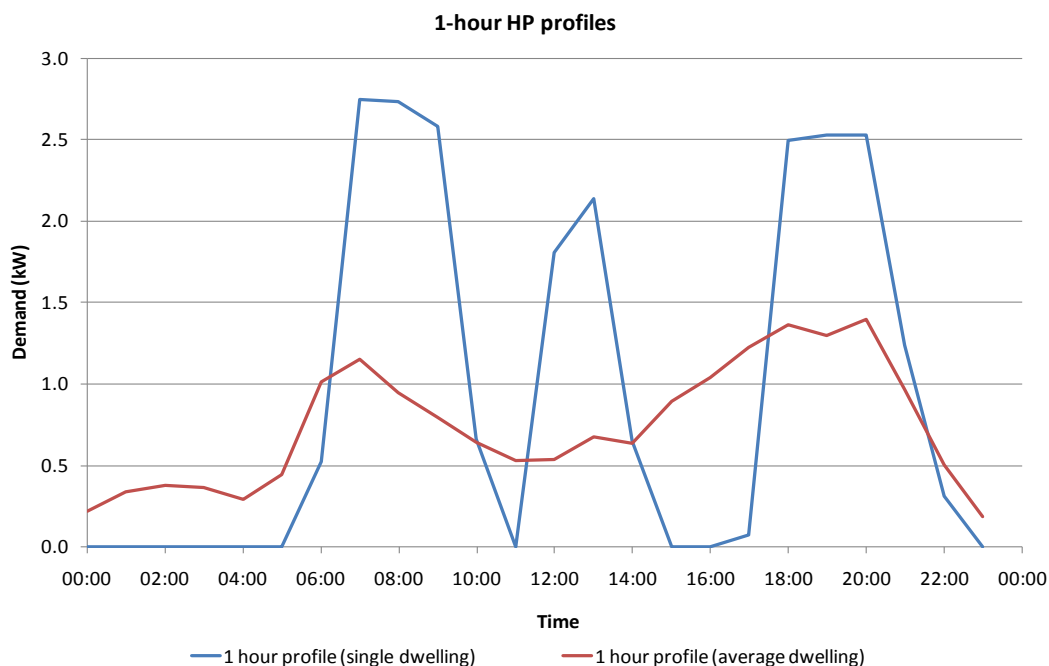


Figure 3-1: Demand profile of a heat pump following the operating pattern of a boiler and aggregate profile of HPs of 21 dwellings in hourly resolution

3.13 Given the characteristics and constraints of heat pumps (i.e. low-temperature operation and reduced rate of heat delivery), a heat pump based system could be accompanied with storage in order to follow heat requirements more closely with lower ratings. That would potentially lead to more continuous operation of heat pumps, which is considered in this work. Heat storage will also provide an opportunity to optimise heat pump operation, not only to meet local heat requirements, but also to contribute to grid management (and support the integration of renewable and less flexible low-carbon electricity generation). Although there are a number of options available it is still uncertain what type and capacity of heat storage might be cost-effective. The analysis shows that heat storage of the capacity of less than 25% of daily heat demand would be sufficient for flattening of national daily demand profile in the case of full penetration of EVs and HPs while taking into account efficiency losses that might accompany the process of storing heat.

3.14 Future analysis would benefit from a more detailed assessment of the impact of different types of heat pumps, different levels of house insulation, various arrangements for backup heating (electricity or gas based peak heat supply) combined with the application of alternative forms of heat storage under different critical outdoor temperature profiles. We are currently in the process of investigating these questions.

National demand profile with electrified heat and transport sectors

3.15 In the Figure 3-2 below a typically cold winter demand profile at the national level is presented. This assumes non-optimised, business-as-usual (BaU) system operation with incorporated heat sector and transport sector with ‘at home’ charging but with no demand response.

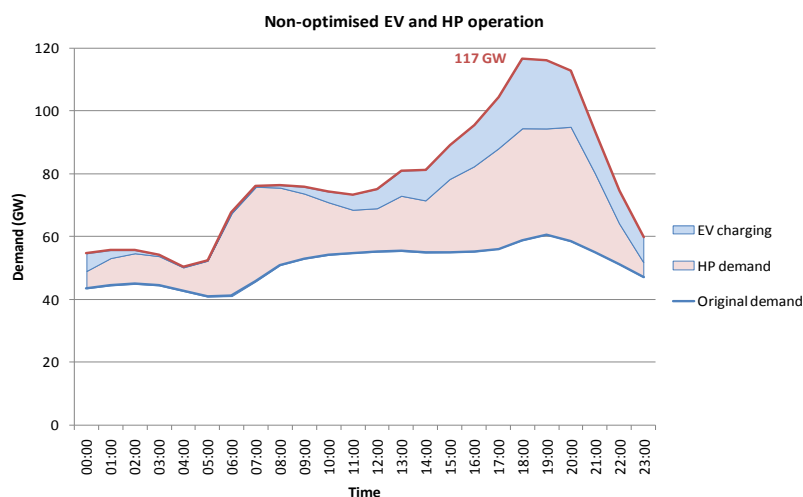


Figure 3-2: Average national load profile with non-optimised EV charging and operation of HPs

3.16 In contrast to Figure 3-2 above, the first two charts in Figure 3-3 illustrate (respectively) the effect of optimising EV charging and HP operation to minimise peak demand, while the third demonstrates the effect of combined optimisation of the two types of responsive demand. In the case of optimised charging of EVs, there is no increase in peak demand. Similarly, in the case of HPs with the presence of heat storage it is possible to flatten the demand profile. Combined optimisation of EV and HP loads can leverage the natural diversity between the Smart demand profiles of EVs and HPs. In other words, domestic HP heat demand is predominantly day-time biased in comparison to ‘at home’ charging of EVs being predominantly night-time biased to enhance the utilisation of electricity infrastructure.

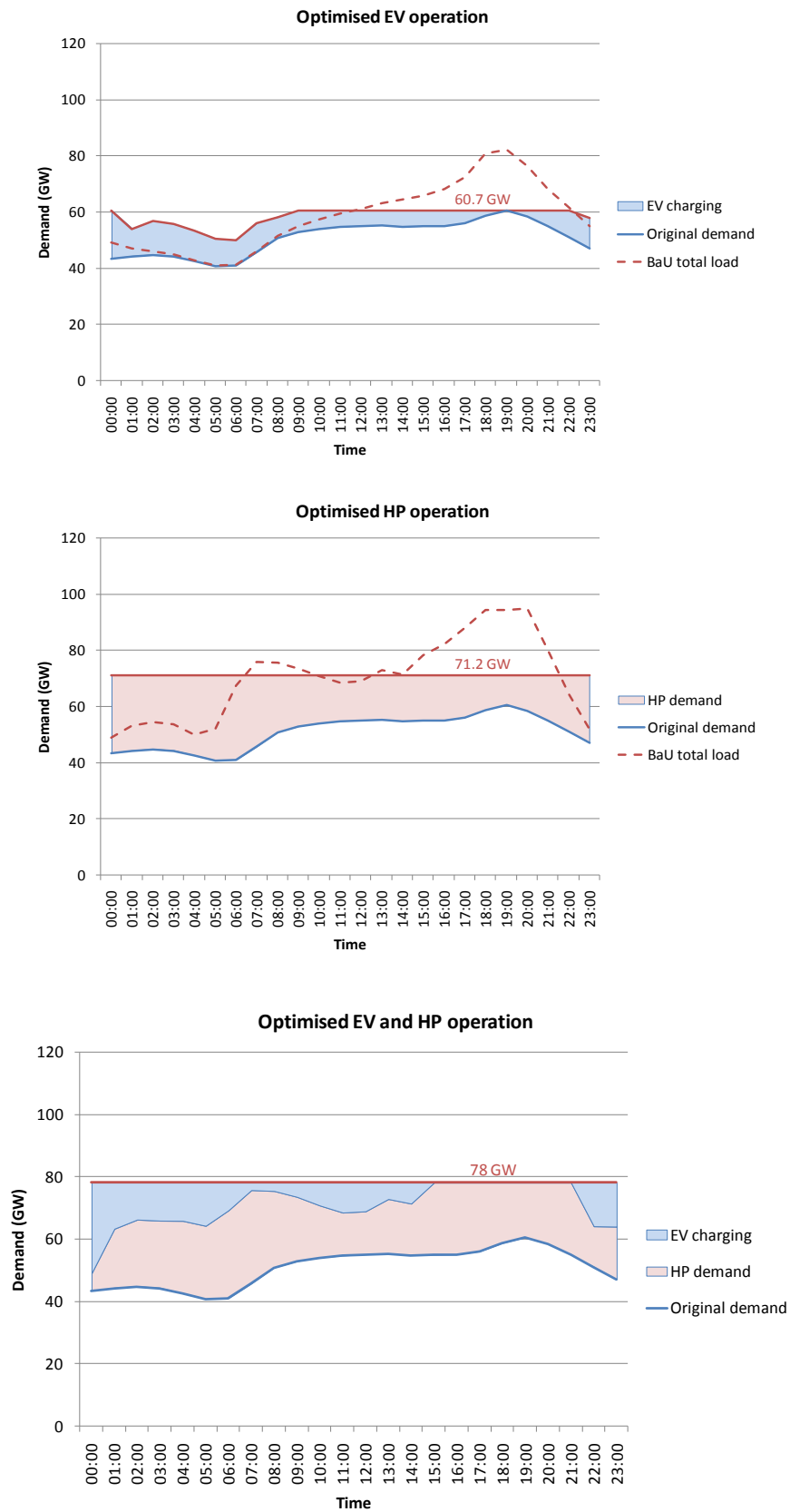


Figure 3-3: Average national load profile with optimised EV charging, optimised HP operation and jointly optimised EVs and HPs

3.17 It is important to note that there will be significant interaction between the optimised demand responses of transport and heat sectors. In the case with heat pumps only, we observe that a significant amount of heat related load would be shifted to the night period. On the other hand, in the combined optimisation with HPs and EVs, electric vehicle demand is shifted to the night while HP loading is only slightly modified from its original profile. This is because shifting HP loads through heat storage will incur energy losses and hence the optimisation would first make use of flexible EV loads while minimising the need to shift HP loads to achieve a flat load profile (which could be accomplished with limited heat storage). This demonstrates the need for a whole system approach when analysing the impact of heat pumps on the electricity system. Clearly, the load impact of electrifying the heat sector can be mitigated by appropriately controlling loads due to electrification of the transport sector, and vice versa, which has not been considered in earlier studies.

3.18 Coordinated management of responsive demand makes it possible to significantly reduce system peaks. In the business-as-usual case, as indicated in Figure 3-4, the energy input requirement of EVs and HPs would increase the energy demand by 52% compared with the original demand. At the same time, the system peak would almost doubles through a 92% increase (out of which 36% is contributed by EVs, and 56% by HPs, as indicated in columns ‘EV only’ and ‘HP only’). In a jointly optimised case (‘EV and HP’ in Figure 3-4) the peak increase is only 29% (for simplicity of presentation we ignore energy losses associated with heat storage that would accompany HP systems). This clearly has a very profound impact on the utilisation of generation and network capacity in the electricity system.

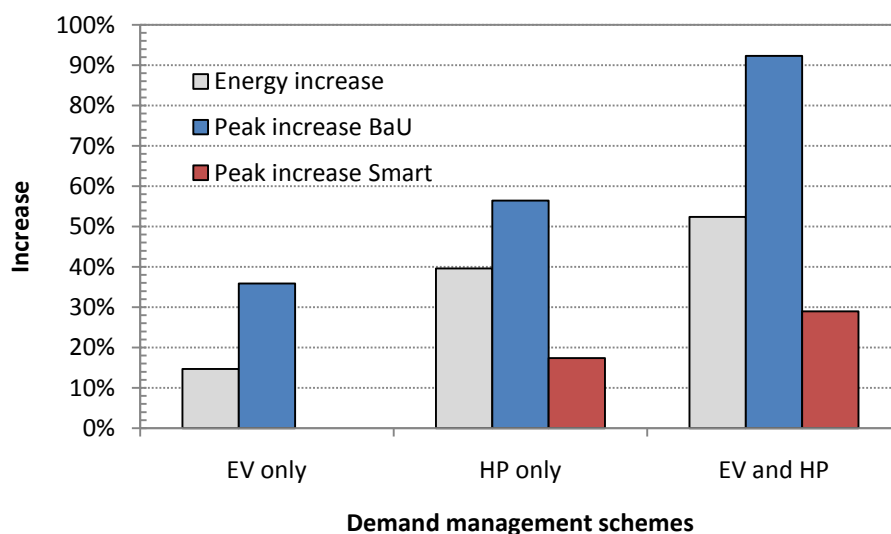
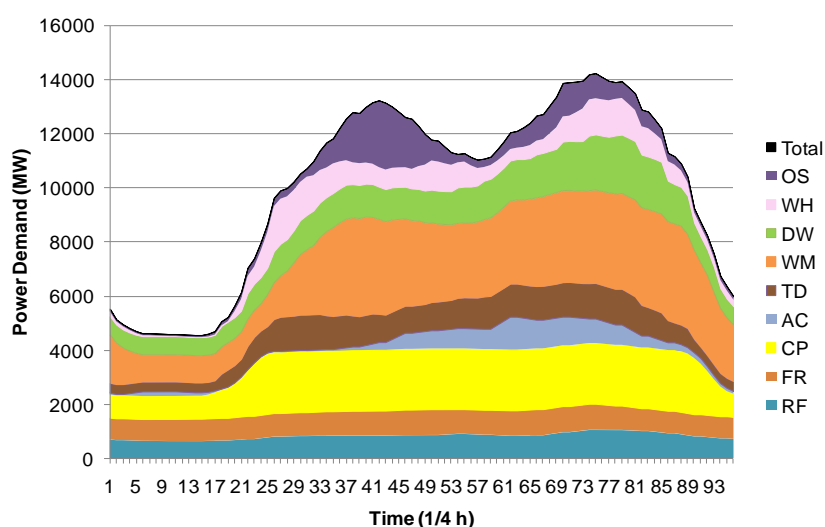


Figure 3-4: Increases in electricity demand and system peak load for different flexible demand management schemes

3.19 It is important to stress that the effect of disproportionately higher increase of peak demand over energy demand is magnified at the local distribution network level due to significant reductions in load diversity. As illustrated in the examples in section 5, network peak demand could more than double for less than 10% increase in energy.

Smart appliances

- 3.20 Household appliances form a significant part of energy consumption, representing around 10% of the total annual energy consumption in the UK. The principle of Smart operation is to modify appliance usage patterns according to the conditions in the system, using smart appliances as sources of demand-side flexibility. Smart appliances would then be able to provide a range of services to the electricity system, such as generation/demand balancing, frequency control, standing reserve, peak reduction and network congestion management.
- 3.21 The analysis here focuses on three types of wet appliances: washing machines (WM), dishwashers (DW), and washing machines equipped with tumble dryers (WM+TD). The data relevant for the use of appliances and the optimisation of their operation has been taken from the Intelligent Energy Europe Smart-A project¹⁰.
- 3.22 An estimate of the diversified daily demand of different appliances in the UK, based on Smart-A data is illustrated in Figure 3-5. It is apparent that some appliances, e.g. refrigerators (RF) and freezers (FR) have a nearly constant demand, while others, such as dishwashers (DW), have a higher demand in the evening. The aggregated system demand from domestic appliances represents a significant share of the system demand, reaching a peak load of 14 GW. As a result, there is considerable potential to use these types of loads to provide demand-side flexibility.



WM – Washing Machine DW – Dishwasher TD – Tumble dryer RF – Refrigerator FR – Freezer
 CP – Circulation Pump AC – Air-Conditioning WH – Water heater OS – Oven and Stove

Figure 3-5: Total demand of domestic appliances in the UK as estimated by EU IEE Smart-A project

- 3.23 In order to quantify the potential benefits of shifting appliance demand cycles in time, we need to establish the number of appliances starting operation at each instance in time. This is established from the diversified demand profile associated with each appliance type together

¹⁰ Details on the project, as well as project reports are available at www.smart-a.org.

with the corresponding operating cycle. An example of this is shown in Figure 3-6 for the UK washing machines data.

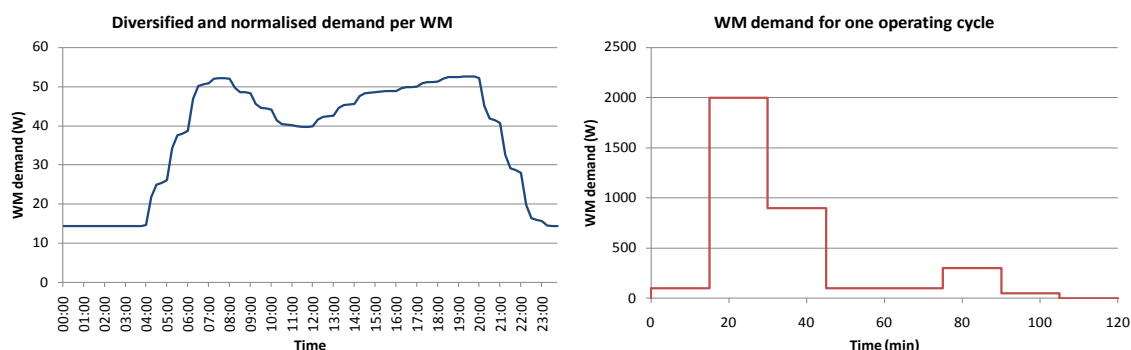


Figure 3-6: Diversified demand of WMs in the UK and consumption per washing cycle

- 3.24 The diversified profile represents the aggregated and normalised demand of an average WM. This suggests that most households use their washing machines early in the morning or in the evening. The WM demand per washing cycle shows that its demand is larger during the water heating phase at the beginning of the cycle, with a smaller demand rise also visible in the spinning phase towards the end of the cycle. This information is used to assess the number of appliances starting their cycles in each time interval.
- 3.25 A summary of their operating parameters and allowed shifting times for the three wet appliances is given in Table 3-3. Customer acceptance surveys conducted in the Smart-A project have been used to support the assumed shifting times tolerated by appliance owners. Penetration rates have been assumed to reflect the current or near-future share of households that own a given appliance type and are willing to allow its flexible operation.

Table 3-3: Operating parameters of smart appliances

Appliance type	Penetration factor	Shifting capability	Cycle duration
Washing machine 1h	20%	1 h	2 h
Washing machine 2h	20%	2 h	2 h
Washing machine 3h	20%	3 h	2 h
<i>Aggregated WM</i>	<i>60%</i>	<i>Up to 3 hours</i>	<i>2 h</i>
Dishwasher	20%	6 h	2 h
Washer-dryer	20%	3 h	4 h

- 3.26 A study was carried out to demonstrate the capability of controllable smart appliances to reduce peak load in a distribution network. The analysis includes the case with the present level of penetration of wet appliances and their full penetration. The two cases are presented in Figure 3-7, with peak reductions of 8.4% and 15.8% respectively.

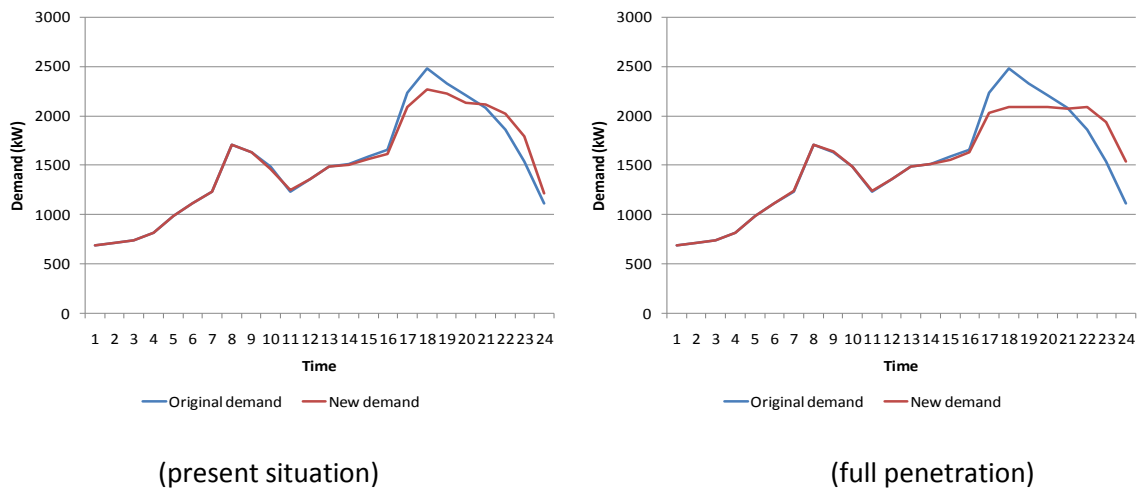


Figure 3-7: Reduced peak load in a distribution network facilitated by smart wet appliances

3.27 To facilitate system-level evaluation of the impact of flexible demand on network operation, a range of optimisation and simulation models have been developed. These models are used to incorporate flexible demand within the optimisation of the generation system at the national level and/or to optimise operation of responsive load at the level of a local distribution network. This was also used to compare the conflict that might arise from optimising the supply side, i.e. operating the generation system without consideration being given to the limitations of the local distribution network.

4 Network operation and reinforcement modelling

- 4.1 Representative high voltage (HV) and low voltage (LV) radial distribution networks have been created using well established Imperial's fractal distribution network design tools [1-2]. Figure 4-1 shows the three LV representative networks used in the study representing a city/town area with a load density of 8 MVA/km², a semi-urban/rural network with a 2 MVA/km² load density and a rural network with a load density of 0.5 MVA/km². The key design characteristics of the representative networks are comparable with those of real distribution networks of similar topologies, particularly in terms of ratings of feeders and transformers used and associated network lengths. Sensitivity assessments carried out confirmed that these parameters are relevant for determining the benefits of incorporating smart metering based demand response into real time distribution network control.

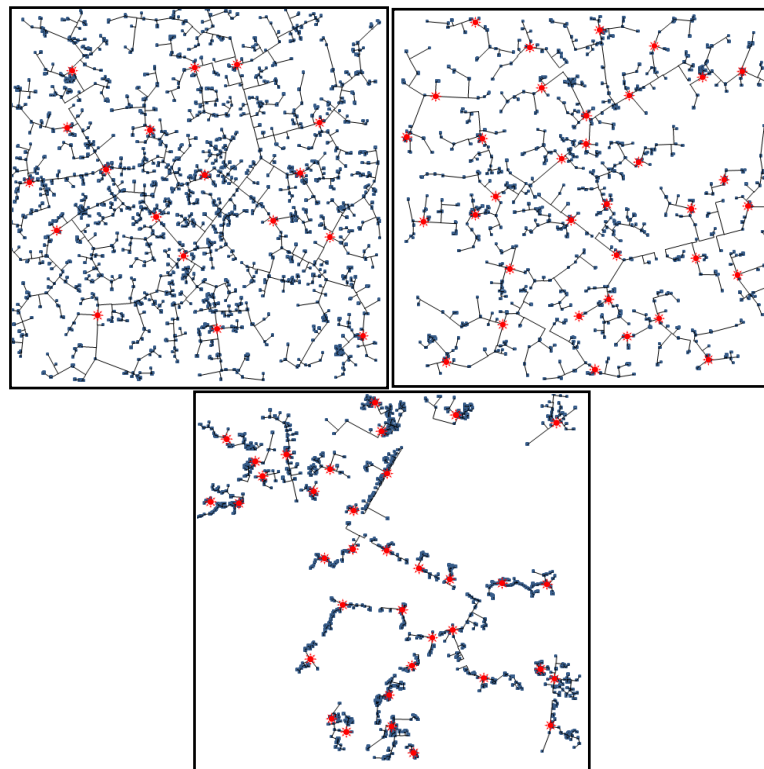


Figure 4-1: Generic representative LV distribution networks

(left to right): city/town area, semi-urban/rural network and a rural network

(blue dots and red stars represent LV consumer and distribution transformers respectively)

- 4.2 Locations of distribution transformers, as sources of supply to LV networks, are at the centre of load clusters, following general design principles aimed at minimising the cost of installed equipment, losses and voltage drops.

4.3 Lengths of the representative LV networks are relatively similar to the networks supplied via ground mounted distribution transformers across a number of DNOs (for which relevant data was available). The average network length associated with a distribution transformer in the GB system is about 1,450 m, while the aggregate average network length of the modelled system is about 1,300 m as shown in Figure 4-2. In practice, variations arise due to the numbers of low voltage cables associated with a transformer and also due to load density (i.e. the ADMD supplied).

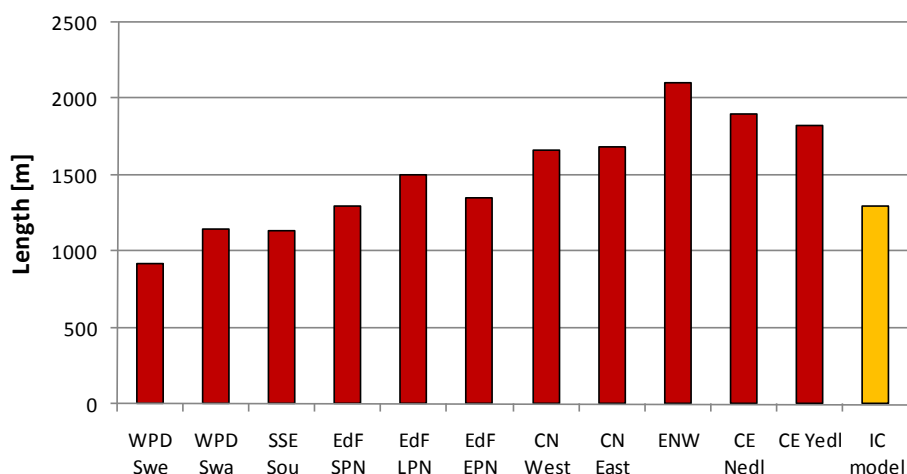


Figure 4-2: DNOs average LV network length per ground mounted distribution transformer

4.4 The HV network model used in this investigation, shown in Figure 4-3, is derived from a modified network topology of Coventry. The total area covered by this HV network model is approximately 134 km², supplying 123,581 consumers via 1094 distribution transformers (blue dots) connected to 16 primary substations 33/11 kV (red squares) via the 11 kV network (blue lines). This network is populated with the three representative LV networks (Figure 4-1), with an assumed proportion of 10% of high load density urban network, 70% of medium load density semi-urban/rural network and 20% of low load density rural network. It can be seen from the figure below, that the area in the centre bottom of the diagram would be representative of an urban area with a high load density, while the top left corner of the diagram would be characteristic of a rural area with a low load density.

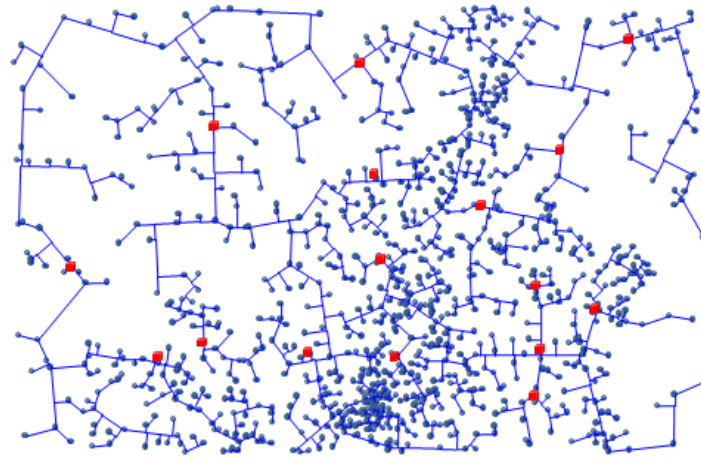


Figure 4-3: HV network model (blue dots and red squares represent distribution transformers and primary substations respectively)

- 4.5 The design of the representative LV and HV network follows the principles of Engineering Recommendation P2/6 [3]. The designed modelled network, comprised of equipment from the set of standard ratings of transformers and underground / overhead lines (UG/OH), satisfies fault level [4] and voltage limit [5] constraints. For AC load flow studies, domestic sector winter and summer working days load profile were used.
- 4.6 Case studies were then performed considering a number of future development scenarios involving penetration of EVs and HPs under the two network operation paradigms: (i) one following the present “unconstrained” network design philosophy with the network control requirements resolved at the planning stage (BaU), and (ii) a second involving active network management in real time facilitated by appropriate smart meter functionality (Smart), optimising response of flexible demand (EVs, HPs and smart appliances); the objective of the optimisation of EV charging and HP operation under ‘Smart’ was to minimise the aggregate peak load (in this context, the benefits identified will be conservative as optimisation in relation to constraints at the individual feeder section level would increase the value of active network control).
- 4.7 The level of network reinforcement required under different levels of penetration of new loads will be driven by both thermal ratings of equipment and network voltage constraints considering the requirements imposed by network design standards. In the case of distribution and primary transformers, relevant British Standards are applied that specify appropriate levels of cyclic rating [6], although it should be noted that the benefits of cyclic rating reduce with flattening of the demand profile.
- 4.8 From the analysis carried out, we have found that a very significant proportion of the total reinforcement cost is driven by loads either exceeding LV feeder thermal ratings or giving rise to voltage variations outside statutory limits. Therefore, two alternative reinforcement strategies are considered: (i) reinforcing overloaded feeder sections while maintaining the number of distribution substations constant and (ii) inserting additional distribution substations in order to reduce the lengths of LV feeders and hence eliminate overloads and inadequate voltages, while reducing the need to reinforce LV feeder sections. It is generally

considered that these two reinforcement policies would provide the boundaries on network reinforcement costs likely to be incurred in practice.

- 4.9 It is also important to reiterate that this study has not taken account of the need for additional, or reinforced, EHV, transmission network and generation infrastructure that would arise from a continued BaU approach. It follows that in practice there would be significant further cost saving benefits associated with the Smart solution.

5 Quantifying the impact of EVs and HPs on distribution network under passive and active network control

5.1 Extensive studies have been carried to quantify the order of magnitude of the impact on the GB electricity distribution network arising from the integration of transport and heat sectors under a variety of conditions. The following driving factors are considered:

- Four different levels of penetration of EVs and HPs (25%, 50%, 75% and 100%) (a sensitivity study was carried out for a 10% penetration level); regarding EVs, average national driving patterns are applied to all local distribution networks; regarding HPs, Grade A insulation levels in dwellings heated by HPs with storage
- Three representative distribution networks (urban, semi urban/rural and rural);
- Two network operation paradigms, passive network operation (BaU) and active network management facilitated with smart metering (Smart);
- The impact of EV commuting patterns on reinforcement of networks supplying business parks/towns and residential areas;
- Two alternative network reinforcement strategies (like-with-like reinforcement and reinforcement based on inserting new distribution substations); and
- Two voltage limit constraints (-6% and -10%) or implicitly, two voltage control strategies.
- Potential conflict between supply and network-driven optimisation of demand side response

Evaluating the impact on LV network

5.2 The three figures below (Figure 5-1 to Figure 5-3) present the percentage of overloaded distribution transformers in the three representative networks under a passive and active network control philosophy, for four different levels of penetration of EVs and HPs.

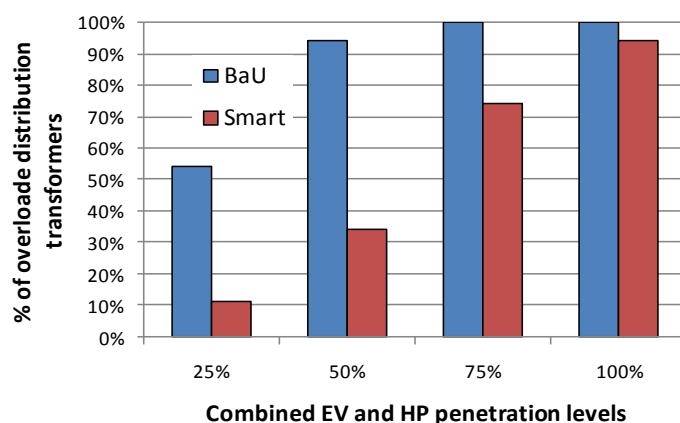


Figure 5-1: Percentage of overloaded distribution transformers (8 MVA/km² case)

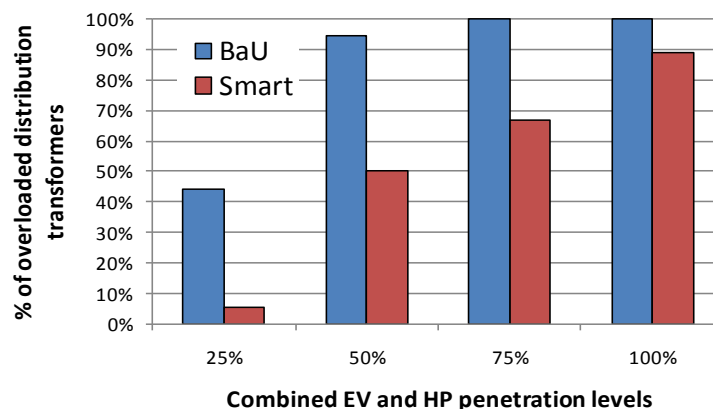


Figure 5-2: Percentage of overloaded distribution transformers (2 MVA/km² case)

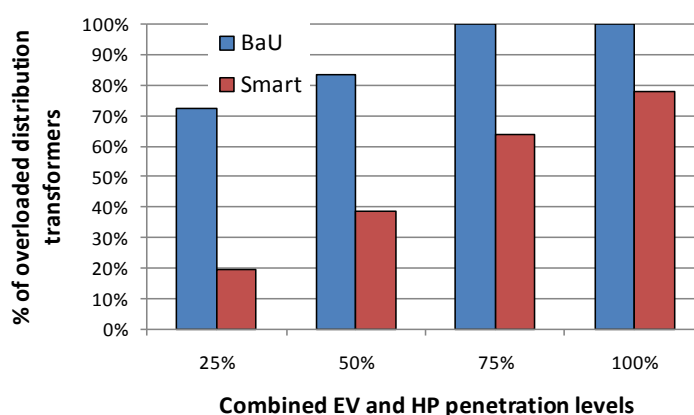


Figure 5-3: Percentage of overloaded distribution transformers (0.5 MVA/km² case)

5.3 As expected, with increasing demand (i.e. increasing penetration of EVs and HPs) the percentage of overloaded distribution transformers also increases. Furthermore, we observe that for smaller levels of penetration the impact of the network control philosophy is more significant. In other words, the difference in percentage of overloaded distribution transformers between BaU and Smart is larger for 25% and 50% penetration levels than for higher levels as the increase in demand for higher levels of penetration is so significant that the scope for avoiding reinforcements is reduced. However, although reinforcement of distribution transformers will be required for higher levels of penetrations of EVs and HPs for both BaU and Smart options, the ratings of the transformers will be significantly lower for the Smart than for the BaU control regime.

5.4 Similarly, the three figures (Figure 5-4 to Figure 5-6) below present the percentage of feeder length that would need to be replaced to eliminate thermal and/or voltage drop violations for the three representative networks under passive and active network operation philosophy. The figures clearly show that passive distribution network operation regime (BaU) will require significantly higher proportion of LV feeder section reinforcement than active (Smart). Our analysis shows that in urban areas, the reinforcement is primarily driven by thermal overloads while for semi-urban/rural and rural networks this is mostly due to excessive voltage drops.

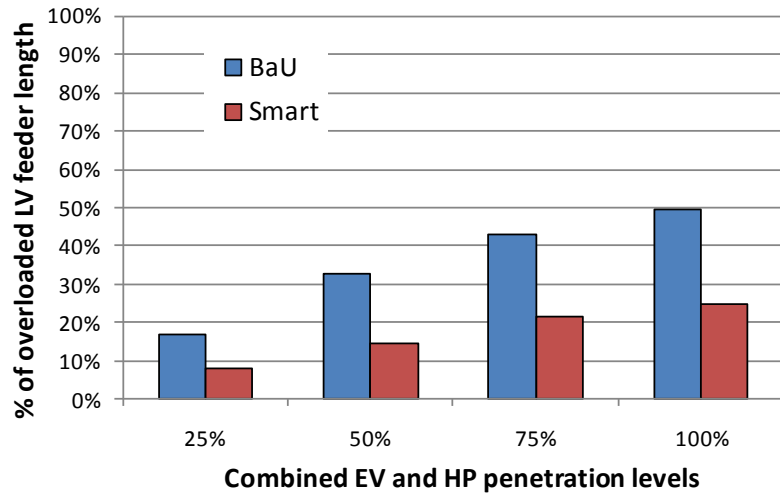


Figure 5-4: Percentage of overloaded LV feeder length (8 MVA/km² case)

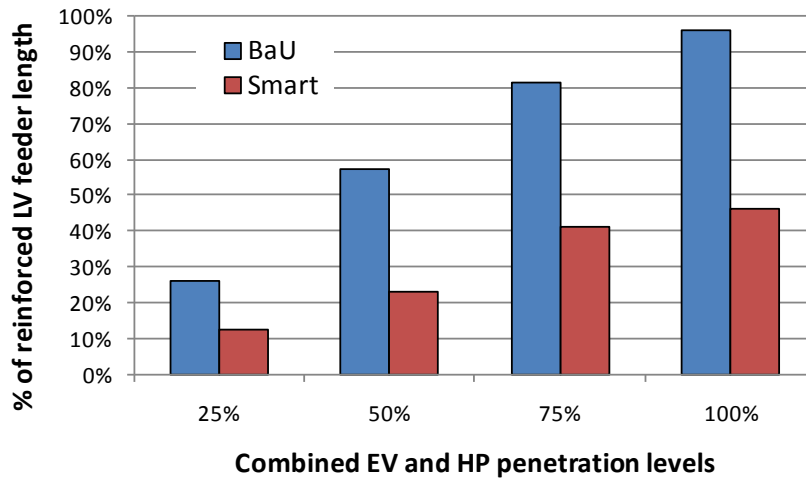


Figure 5-5: Percentage of reinforced LV feeder length (2 MVA/km² case)

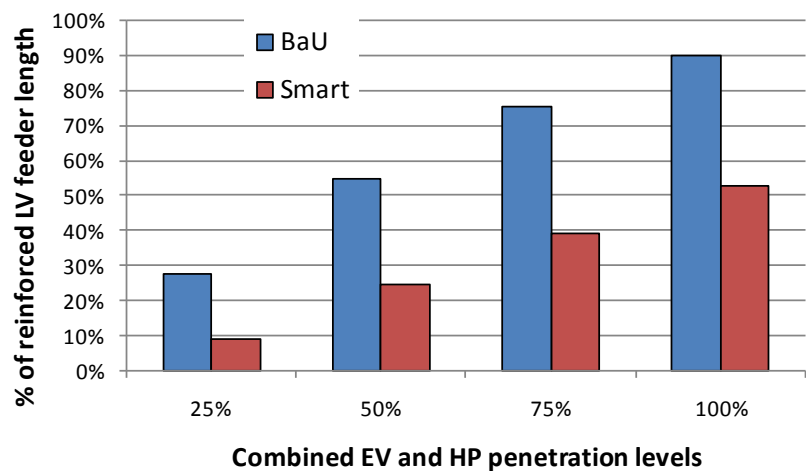


Figure 5-6: Percentage of reinforced LV feeder length (0.5 MVA/km² case)

Analysing the impact of EV and HP separately

5.5 We have also separately considered EVs and HPs to analyse their individual impacts on network loading and hence the need for network reinforcement. The sensitivity analysis was carried out on a dominant semi-urban/rural LV network with a load density of 2 MVA/km². The results are shown in Figure 5-7 and Figure 5-8. The results show similar trends to the combined penetrations of EVs and HPs, with Smart operation resulting in a significant reduction in overloads over the BaU paradigm.

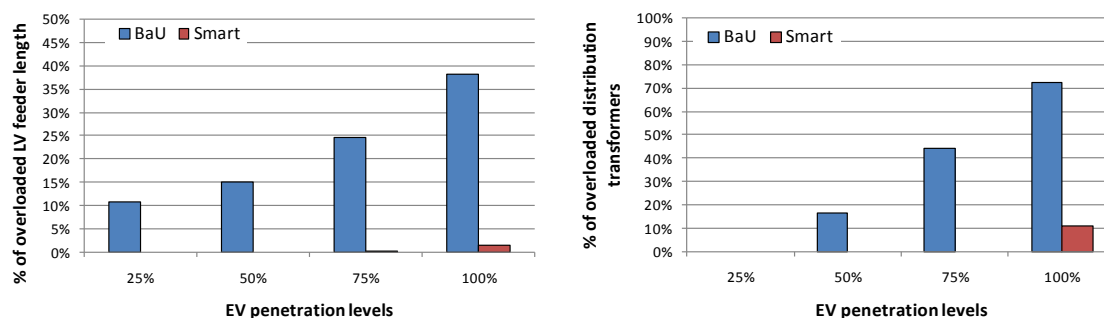


Figure 5-7: Percentage of overloaded LV feeder length and distribution transformers for different penetrations of EVs assuming average driving patterns (no HPs)

5.6 From Figure 5-7 we observe that the benefits of Smart operation are very significant even for very large levels of penetration, given the flexibility of transport demand (relatively low energy requirements, relatively high power ratings of batteries combined with a very significant proportion of time available for charging). In the case of HPs, the benefits are more significant for modest penetration levels, and saturate for high levels of uptake (Figure 5-8). This is expected as the energy requirements of the heat sector are more significant and accommodating considerable increases in energy delivered will lead to overloads.

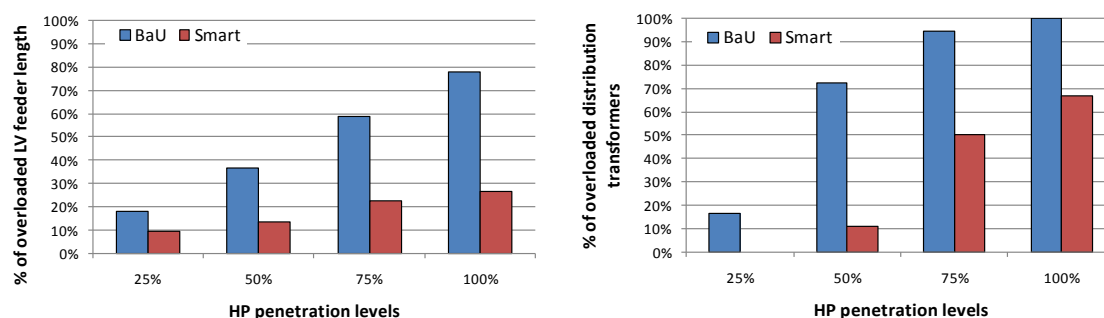


Figure 5-8: Percentage of overloaded LV feeder length and distribution transformers for different penetrations of HPs (no EVs)

5.7 It follows from the above that under a scenario wherein EV penetration levels initially exceed HP penetration levels (or vice versa to a lesser extent) there will still be a significant benefit in adopting a Smart approach over a BaU approach.

Evaluating the impact on HV network

5.8 The three LV representative networks were used to populate the HV network model presented in Figure 4-3. The figures below (Figure 5-9 and Figure 5-10) present percentages of overloaded primary transformers (33/11kV) and the percentages of length of HV feeders that would need to be replaced to eliminate thermal and/or voltage drop violations under a passive and an active network control philosophy. The results show similar trends to those observed in the case of LV networks. For smaller levels of penetration the impact of the network control philosophy is more significant. Note that the difference in percentage of overloaded primary transformers between BaU and Smart is quite larger for lower levels of penetration, while for larger penetrations the two operation philosophies converge (however, significantly larger ratings will be needed for a passive compared with an active network management approach).

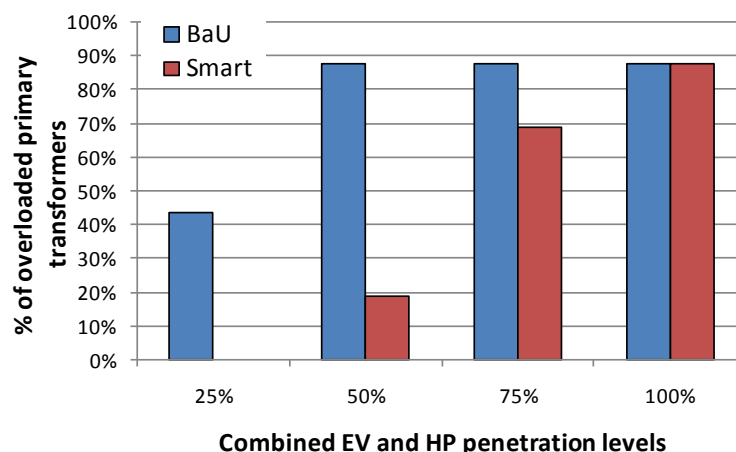


Figure 5-9: Percentage of overloaded primary transformers

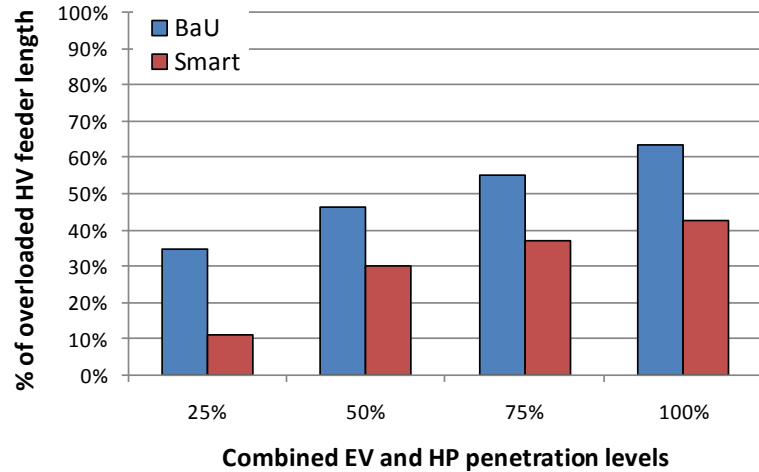


Figure 5-10: Percentage of overloaded HV feeder length

Impact of commuting driving patterns

- 5.9 In the above analysis it was assumed that average driving patterns observed at the national level would be statistically similar to those at the local level. In this section we analyse the potential impact of driving patterns associated with commuting to a town/business park area in the morning and making return journeys in the evening. This will lead to more concentrated EV charging in the morning hours, given the typical arrival times to town/business park areas of between 8am and 9am and evening charging driven by typical home arrival times of between 6pm and 8pm.
- 5.10 In this study we analyse a commercial district area considering both BaU and Smart mode of operation. As expected, a significant increase in morning peak demand under BaU would be driven by concentrated EV charging, as illustrated in Figure 5-11: BaU (left) and Smart (right) demand profile in a commercial district (1 km²) driven by charging of 5,000 EVs following arrivals to work below. On the other hand, a very flat profile can be obtained if charging is optimised.

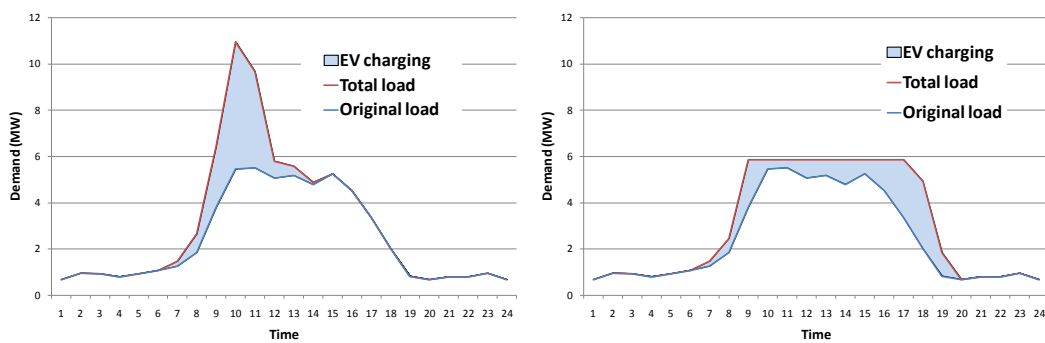


Figure 5-11: BaU (left) and Smart (right) demand profile in a commercial district (1 km²) driven by charging of 5,000 EVs following arrivals to work

5.11 Figure 5-12 contrasts the increases in network peak demand for BaU and Smart mode of operation. Clearly, not incorporating demand side in network real time operation will result in massive degradation in network asset utilisation.

5.12 Figure 5-13 shows the percentage of low voltage (LV) and high voltage (HV) networks, and primary and distribution transformers, that would be overloaded under both a BaU and a Smart regime of EV charging. The results indicate that smart charging for EV is critical to mitigate expensive network reinforcement. By maintaining the BaU approach, the network reinforcement cost could be 8 times higher than under an active network control regime.

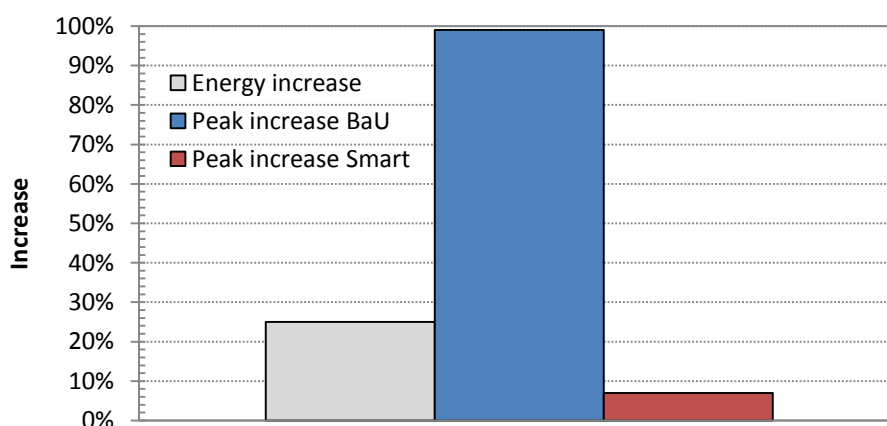


Figure 5-12: Increases in electricity demand and local network peak load

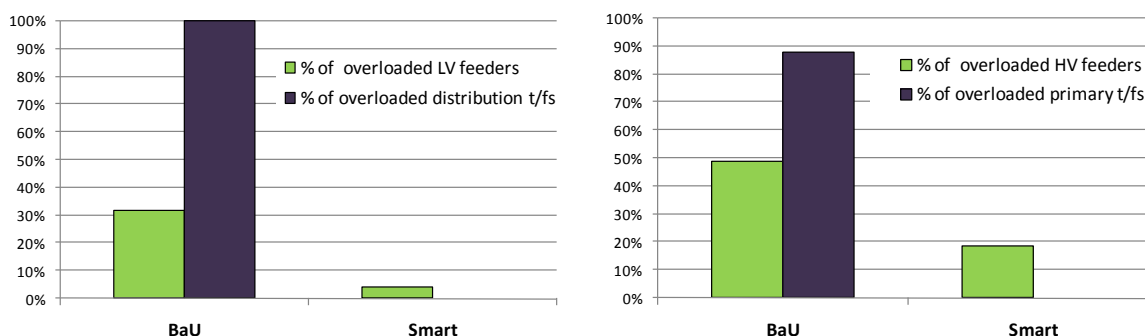


Figure 5-13: Percentage of overloaded distribution transformers and LV feeders (left) and primary substations and HV feeders (right) under BaU and Smart operating regime in a commercial district driven by charging of EV following arrivals to work

5.13 Figure 5-14 shows the changes in demand profile for the case in a residential area driven by the EV charging when people return home from work for both BaU and Smart modes of operation. As expected, peak demand is observed in the evening as charging is assumed to start upon arrival at home from work. We assume that evening charging will recover the energy of the return journey only, while the energy associated with the journey to work is

recovered through charging during working hours at the workplace). Under a Smart operating regime, this demand peak (and hence a massive network reinforcement cost) can be avoided as shown in Figure 5-15.

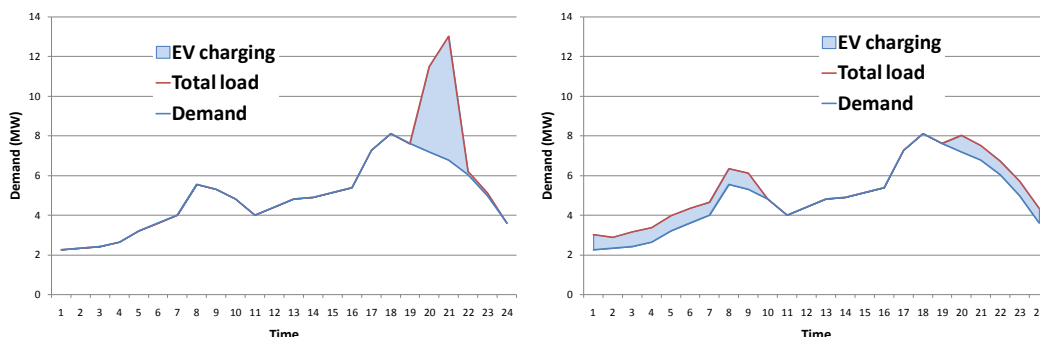


Figure 5-14: BaU (left) and Smart (right) charging in a residential area (8,000 properties) driven by charging of 5,000 EVs when people return from work

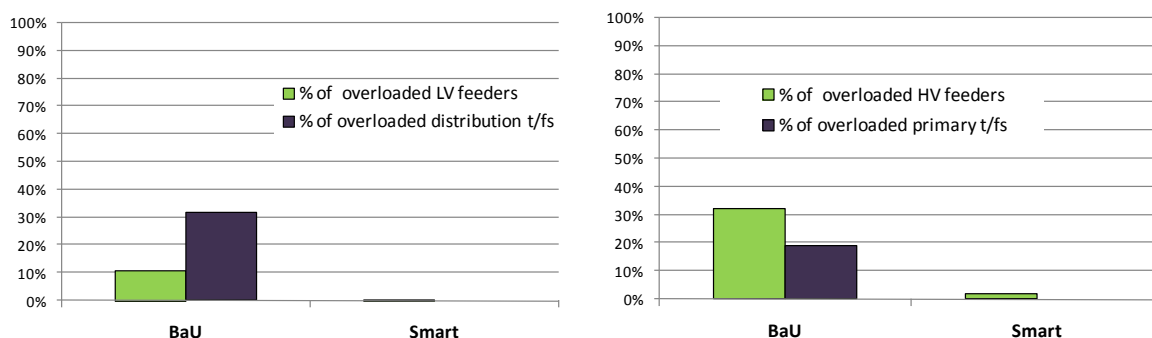


Figure 5-15: Percentage of overloaded distribution transformers and LV feeders (left) and primary substations and HV feeders (right) under BaU and Smart operating regime in residential area driven by charging of EV following return from work

Potential conflict between supply and network-driven optimisation of demand side response

5.14 In addition to using flexible demand to reduce peak loads and consequently improve generation and network capacity utilisation it may also be desirable for demand to respond to opportunities in the energy market. Demand response could be optimised to maximise the benefits from time varying energy prices. An example to illustrate the potential conflict between maximising the network and energy benefits for the case of flexible EVs is given in Figure 5-16. The diagram on the left is the same as in Figure 3-3, depicting optimised EV charging with the objective of reducing system peak. In the diagram on the right, however, the objective is to minimise system operation costs in a potential future situation where high wind generation output coincides with peak demand. In this supply-driven optimisation of EV

charging, much of EV consumption is shifted towards the time around system peak to make full use of available wind energy.

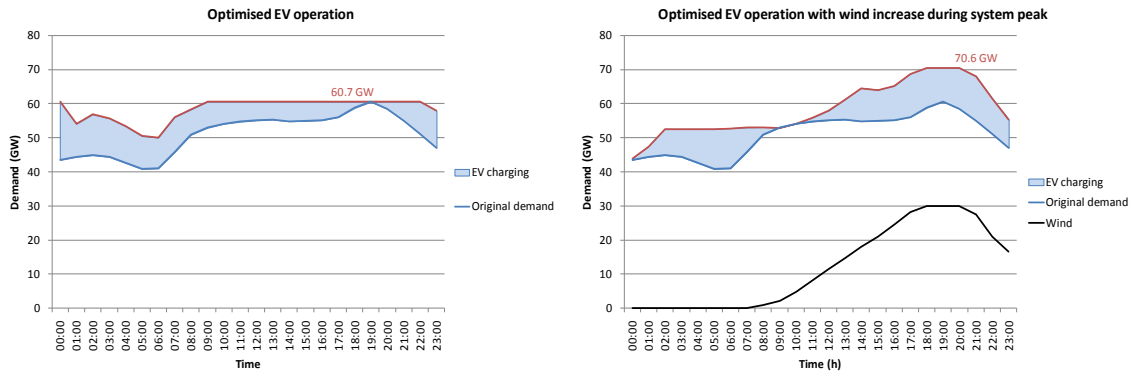


Figure 5-16: Network-driven vs. price/supply-driven management

5.15 With a large number of EVs being charged during peak hours (driven by supply price signals) the stress on the distribution networks will be significant. Figure 5-17 quantifies the impact on the LV distribution network in terms of the percentage of overloaded network feeders and transformers for the two cases depicted in Figure 5-16. Managing EV charging with the sole objective of optimise energy supply results in a much higher proportion of overloaded feeders (32% vs. 1%) and transformers (60% vs. 11%), which would also be reflected in appropriately higher network reinforcement costs. This simple example illustrates that independent operation of the electricity market (i.e. continuing with an “unconstrained” trading philosophy) without due consideration of distribution network limitations will potentially be suboptimal in terms of the overall efficiency (and therefore cost) of the end-to-end electricity delivery chain.

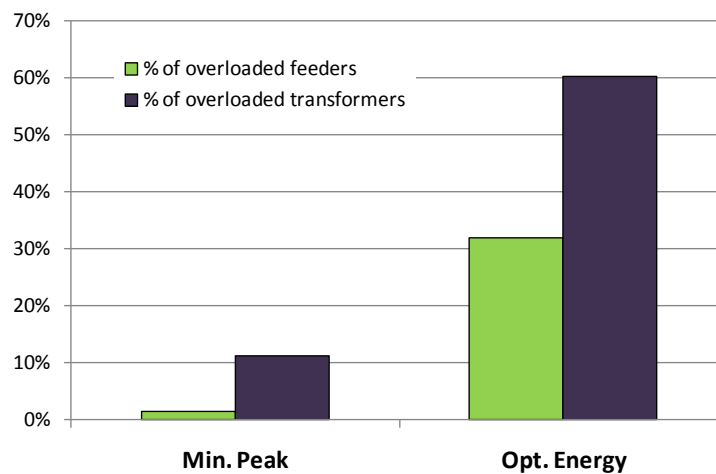


Figure 5-17: Percentage of overloaded elements for two conflicting strategies

Impact of voltage drop limits and active LV network voltage control

5.16 Our analysis has confirmed that a relatively significant proportion of network reinforcement cost may be driven by voltage constraints, particularly in semi-urban/rural and rural networks. By relaxing the voltage drop limits from -6% to -10% we implicitly assessed the potential for reducing network reinforcements through introducing LV voltage control facilities such as in-line voltage regulators or distribution transformers with an on-line tap changing capability

5.17 Figure 5-18 shows the percentage of LV feeder lengths that would need reinforcement for different levels of voltage constraints under a BaU and a Smart mode of network operation for 50% of EV and HP penetration (a semi-urban/rural network is considered). If the voltage limit constraint were relaxed to say 10%, the percentage of feeder length reinforcement driven by voltage constraint decreases. As expected, the need for feeder reinforcement under the Smart operating regime is significantly lower than for the BaU mode of operation.

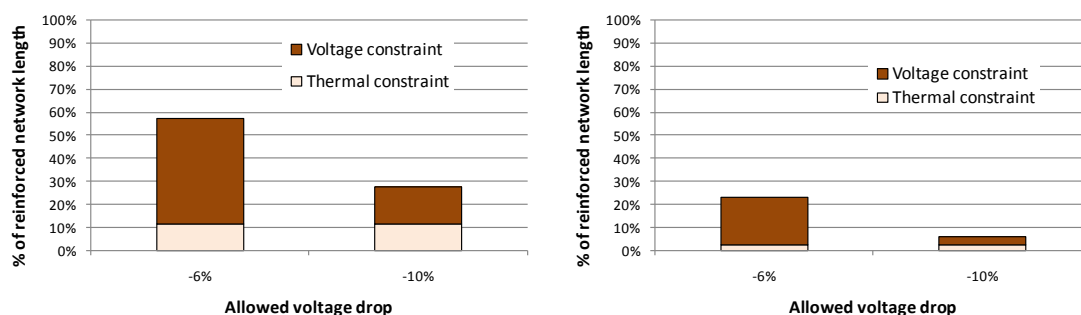


Figure 5-18: Percentage of reinforced LV feeder length for BaU (left) and Smart (right) for different voltage limit constraints (50% EV and HP penetration on 2 MVA/km²)

5.18 As expected, savings from relaxing voltage drop limits or installing LV voltage control facilities are lower when the penetration of EVs and HPs increases to 100%, as shown in Figure 5-19. However, real-time LV voltage control in combination with real-time demand response supported by appropriate functionality of smart metering, can avoid reinforcements for a significant proportion of the LV network.

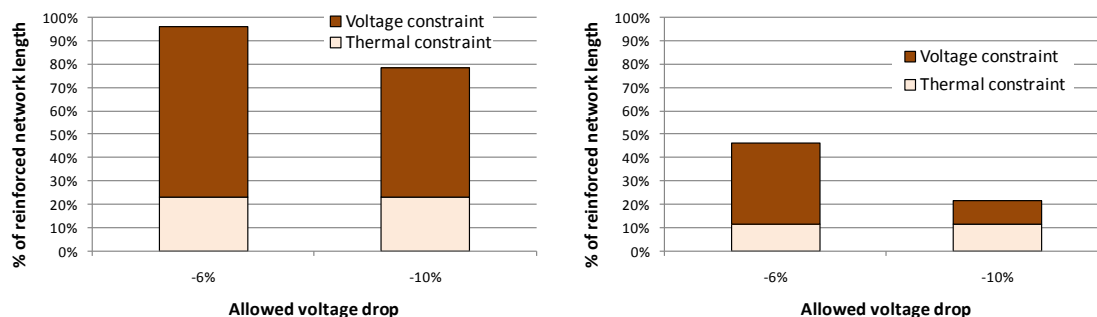


Figure 5-19: Percentage of reinforced LV cable length for BaU (left) and Smart (right) for different voltage limit constraints (100% EV and HP penetration on 2 MVA/km²)

5.19 At this stage we have not studied the cost savings that might result from allowing a 10% voltage drop (which would potentially require a modification to the ESQC Regulations) or of alternative LV voltage regulation strategies as described above. This will require a detailed study exploring the feasibility of allowing a wider variation in LV system voltage in terms both of appliance compatibility and overall energy efficiency (noting for example that EV charging load is clearly energy led – meaning that a reduced terminal voltage would simply extend the length of the charging cycle, possibly leading to critical loss of overall diversity in EV charging load). It is also predicted that with greater penetrations of DG on HV and LV networks (for example incentivised by the imminent introduction of Feed-in Tariffs) it will be efficient to make increasing use of the available statutory voltage bandwidth, leaving little scope for further extending the boundaries to avoid reinforcement.

Network reinforcement strategies

5.20 In order to deal with overloads of feeders and transformers and inadequate network voltages network caused by the uptake of transport and heat demand, two network reinforcement strategies are investigated: (i) one is based on reinforcing feeders with inadequate voltage profiles or feeder sections with thermal overloads, while maintaining the original structure of the network. This like-with-like reinforcement strategy would correspond to an upper bound on network reinforcement cost; (ii) an alternative network reinforcement strategy involves injecting additional distribution transformers that split the existing LV network hence reducing the length and loading of the feeders; given that the total distribution network reinforcement cost are dominated by LV network reinforcement, this would correspond to a lower bound on network reinforcement costs.

5.21 From Figure 5-20 we observe that the potential financial benefits of reinforcement policy (ii) are potentially very significant. The overall reinforcement scheme costs as a result of inserting additional distribution transformers with accompanying switchgear would normally be significantly lower, amounting to approximately one third of the cost of like-with-like replacement. We should however mention that this option may not be available in all circumstances due to various physical constraints that may limit building new substations.

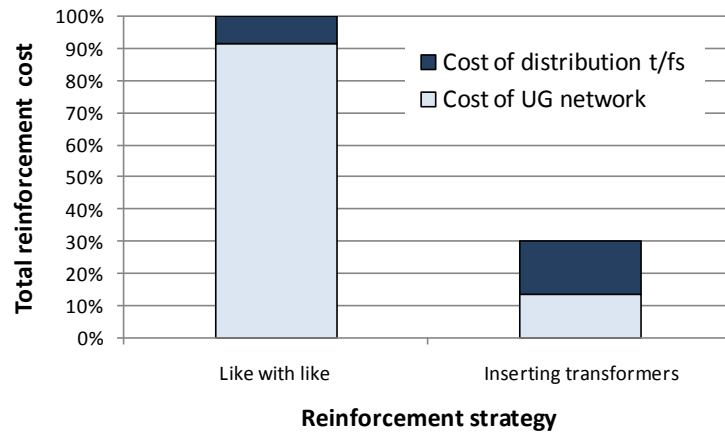


Figure 5-20: Total LV network reinforcement cost for reinforcement strategies (100% EV and HP penetrations)

6 Quantifying the value of smart meter-enabled active control of UK distribution networks

- 6.1 For consistency, the costs associated with reinforcement of individual network components, including LV and HV feeders as well as distribution and primary transformers, are taken from Ofgem’s DPCR5 Final Proposals [7].
- 6.2 For the sample network described in Figure 4.3, the costs of network reinforcement for each of the four penetration levels, and for each of the two (BaU and Smart) control philosophies, are presented in Figure 6-1. In this analysis a central case with a like-with-like network reinforcement approach is considered with a maximum allowed voltage drop in LV networks of 6%. As expected, the costs increase with the level of penetration of EVs and HPs, with the total costs being dominated by LV network costs.

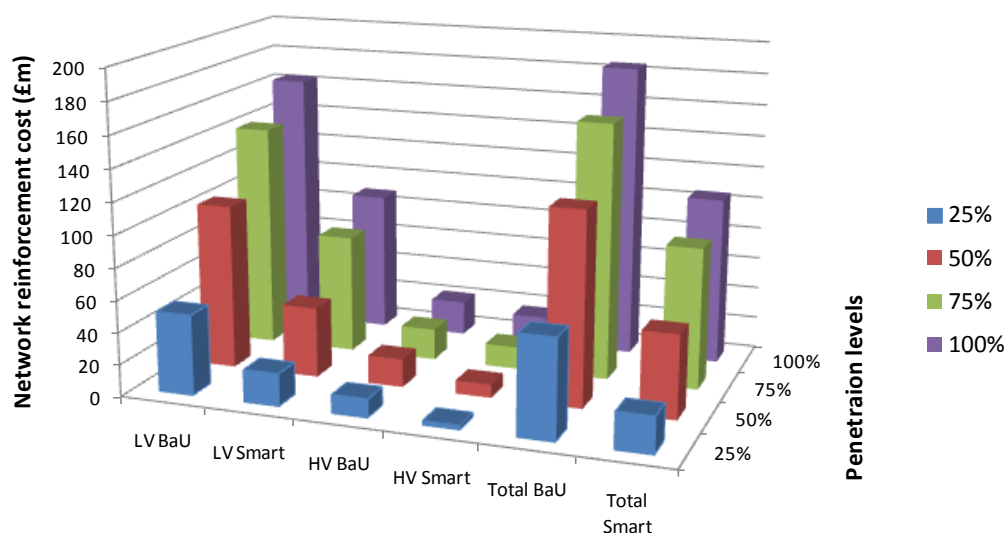


Figure 6-1: Coventry network reinforcement cost

- 6.3 Table 6-1 and Table 6-2 show the network reinforcement cost (under a like-with-like replacement strategy) across the entire GB distribution network for a passive (BaU) and an active distribution network operating regime (Smart).

Table 6-1: Estimated GB Network reinforcement costs under a BaU operating paradigm

Penetration levels	LV (£bn)			HV (£bn)			Total (£bn)
	Transformer	Feeder	Total	Transformer	Feeder	Total	
10%	0.7	3.7	4.4	0.3	0.4	0.7	5.1
25%	2.1	8.5	10.6	0.8	1.6	2.4	13.0
50%	3.4	18.4	21.8	1.6	2.2	3.7	25.5
75%	3.8	25.9	29.7	1.6	2.6	4.1	33.8
100%	3.8	30.6	34.3	1.6	3.0	4.5	38.8

Table 6-2: Smart network reinforcement costs for the entire GB HV and LV distribution system

Penetration levels	LV (£bn)			HV (£bn)			Total (£bn)
	Transformer	Feeder	Total	Transformer	Feeder	Total	
10%	0.3	1.5	1.8	0.1	0.3	0.4	2.2
25%	0.4	3.8	4.2	0.0	0.5	0.5	4.7
50%	1.7	7.6	9.3	0.3	1.4	1.8	11.1
75%	2.5	13.2	15.7	1.2	1.7	3.0	18.7
100%	3.2	15.4	18.6	1.6	2.0	3.6	22.2

6.4 Figure 6-2 shows the total UK electricity distribution network reinforcement cost for BaU and Smart operating regime. We observe that the total network reinforcement costs under BaU operating regime are about 2.5-3 times higher than under Smart, while this ratio drops to about 1.8 for higher penetrations levels. This is summarised in Figure 6-2 below.

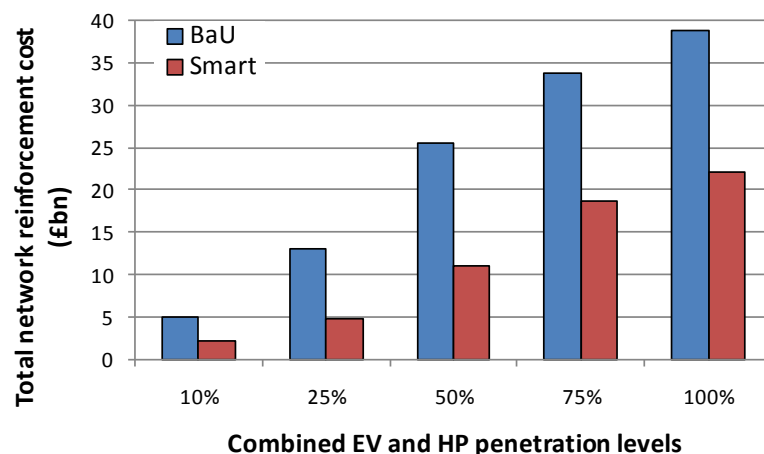


Figure 6-2: Total UK (LV and HV) network reinforcement cost

6.5 Table 6-3 presents the value associated with an active (Smart) network operation regime achieved by reducing network reinforcement costs through optimising demand response facilitated by appropriate smart meter functionality.

Table 6-3: Value of smart meter-enabled active control of GB distribution networks

Penetration levels	LV (£bn)			HV (£bn)			Total (£bn)
	Transformer	Feeder	Total	Transformer	Feeder	Total	
10%	0.3	2.2	2.5	0.2	0.2	0.4	2.9
25%	1.7	4.7	6.3	0.8	1.1	1.9	8.2
50%	1.7	10.8	12.5	1.2	0.8	2.0	14.5
75%	1.3	12.7	14.0	0.3	0.8	1.2	15.1
100%	0.6	15.2	15.7	0.0	1.0	1.0	16.7

6.6 We have also evaluated the Net Present Value (NPV) of the smart meter enabled active control of GB distribution networks, under different scenarios of uptake of EVs and HPs. This represents the NPV of avoided network reinforcement cost. A discount rate of 3.5%, as used for the Government infrastructure, is assumed in this analysis (this value has been recently used by the Electricity Networks Strategy Group [8]).

6.7 Five scenarios with different levels of penetration of EVs and HPs have been considered as shown in Figure 6-3. This is consistent with the Government-projected cumulative penetration of 1.7 million cars by 2020 (approximately 5% penetration) [9]. Starting from year 2020 to 2030, scenario 1 to scenario 4 represents different levels of uptakes of EVs and HPs.

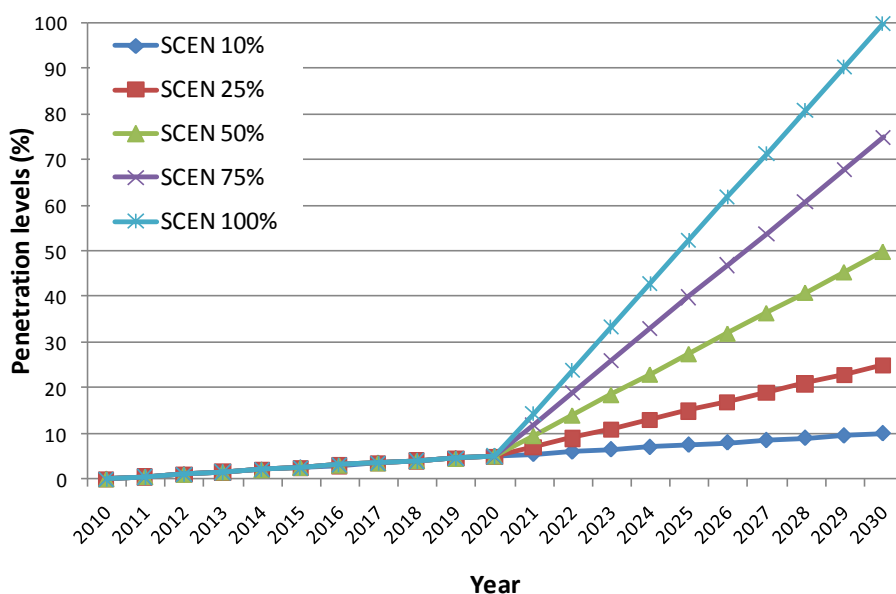


Figure 6-3: Penetration scenarios for combined EVs and HPs

6.8 We conducted the analysis both with a like-with-like network replacement strategy (upgrading the network components to the new required capacity and maintaining the existing network topology) and with a strategy that is based on splitting LV network by inserting new distribution substations (aimed at eliminating overloads on LV networks by shortening LV feeder lengths). The alternative reinforcement strategies provide the estimates of boundaries

of network reinforcement costs. The like-with-like approach would give an approximate upper boundary, while reinforcement based on LV network splitting achieved through inserting additional distribution transformers would indicate a lower boundary of the value of smart meter-enabled active network management capability. In this assessment we have also included an estimate of the value of controlling ‘wet’ appliances to support active network management.

6.9 From Table 6-4 we observe that for the entire GB distribution network the value in NPV terms of Smart management of demand, enabled by an appropriately specified smart metering system, is between £0.5bn and £10bn, across all scenarios considered.

Table 6-4: GB Network reinforcement costs for two network control approaches and the associated value of smart meter-enabled active control

Scenarios	NPV costs LV (£bn)		NPV costs HV (£bn)		NPV Value of Smart (£bn)
	BaU	Smart	BaU	Smart	
SCEN 10%	0.75 - 2.48	0.30 - 0.98	0.06 - 0.20	0.03 - 0.08	0.48 - 1.62
SCEN 25%	1.90 - 6.26	0.70 - 2.32	0.20 - 0.66	0.04 - 0.13	1.36 - 4.47
SCEN 50%	3.76 - 12.4	1.48 - 4.88	0.30 - 1.00	0.13 - 0.42	2.45 - 8.10
SCEN 75%	5.08 - 16.72	2.47 - 8.12	0.34 - 1.11	0.22 - 0.71	2.73 - 9.00
SCEN 100%	5.85 - 19.27	2.91 - 9.59	0.37 - 1.21	0.26 - 0.85	3.05 - 10.04

6.10 The increase in network utilisation, which would be achieved through an active network control philosophy, would lead to an increase in distribution network losses, particularly for higher levels of penetration of EVs and HPs; however, the estimated NPV of the increased cost of losses over the period under consideration is demonstrated not to be material.

6.11 We also further conducted sensitivity analysis of the importance of incorporation of demand side into real time network operation and considered EV only scenarios for 10% and 25% as shown in Figure 6-4, assuming no uptake of heat pumps. Four different densities for each of the EV penetration levels are considered as shown in Table 6-5 and Table 6-6 respectively.

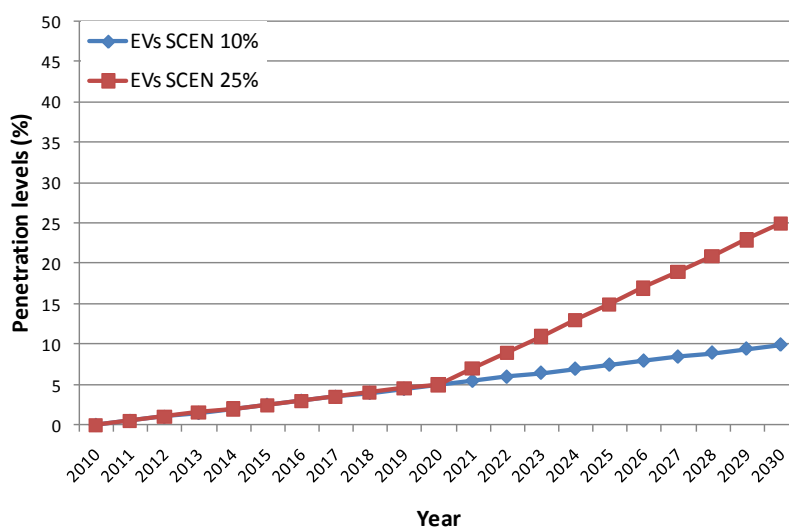


Figure 6-4: Penetration scenarios for EVs only

Table 6-5: EV densities considered for 10% penetration levels

Density cases	Dens -1	Dens -2	Dens -3	Dens -4
Average EV penetrations %	25%	50%	75%	100%
Area %	40%	20%	13%	10%

Table 6-6: EV densities considered for 25% penetration levels

Density cases	Dens -1	Dens -2	Dens -3	Dens -4
Average EV penetrations %	25%	50%	75%	100%
Area %	100%	50%	33%	25%

6.12 For example, case Dens-1 in Table 6-5 represents a situation of 25% EV penetration level occupying 40% of the network, while the remaining 60% of the network is EV free (resulting in 10% EV penetration on average, considering the entire system). Similarly, Dens-4 indicates an extreme situation with 100% penetration of EVs in 10% of the network. Various densities are considered as it is expected that EV penetration levels may vary considerably across the system (i.e. some networks may experience high penetration levels while some very low penetration rates).

6.13 This analysis was then used to establish the value of smart meter-enabled active control of UK distribution networks for the two penetration levels, as presented in Table 6-7 and Table 6-8 respectively. We observe that the reinforcement cost required in a Smart operating regime is negligible (i.e. almost all network reinforcement costs can be avoided by changing the network operation philosophy).

Table 6-7: Value of smart meter-enabled active control of UK distribution networks for 10% EV penetration

EV 10%	LV (£bn)			HV (£bn)			Total (£bn)
	Transformer	Feeder	Total	Transformer	Feeder	Total	
Dens -1	0.00	1.35	1.35	0.00	0.10	0.10	1.46
Dens -2	0.09	0.94	1.03	0.00	0.12	0.12	1.16
Dens -3	0.17	1.01	1.18	0.04	0.10	0.14	1.32
Dens -4	0.17	1.14	1.31	0.04	0.08	0.12	1.43

Table 6-8: Value of smart meter-enabled active control of UK distribution networks for 25% EV penetration

EV 25%	LV (£bn)			HV (£bn)			Total (£bn)
	Transformer	Feeder	Total	Transformer	Feeder	Total	
Dens -1	0.00	3.38	3.38	0.00	0.26	0.26	3.64
Dens -2	0.23	2.35	2.58	0.00	0.31	0.31	2.90
Dens -3	0.42	2.53	2.94	0.11	0.24	0.36	3.30
Dens -4	0.43	2.85	3.28	0.10	0.20	0.30	3.58

6.14 From Figure 6-5 we observed that the total LV and HV NPV value for 10% and 25% EV penetration of different density mixes are in the range of about £0.25bn to £2.3bn. This clearly indicates that value of advanced smart metering functionality, that would facilitate real time management of responsive demand is considerable, even in extreme scenarios of very low penetration of EVs and a complete absence of heat pumps.

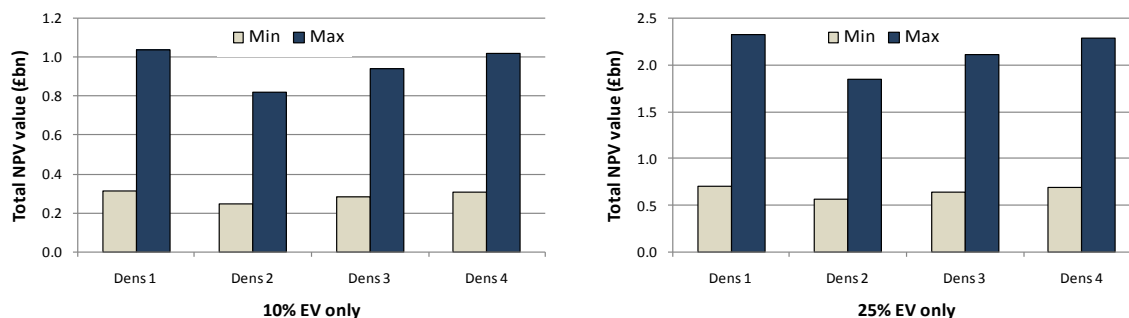


Figure 6-5: Total NPV value (LV+HV) for 10% and 25% EV only scenarios

6.15 Clearly, the opportunities for optimising demand response in relation to network constraints will be very significant. It is important however to appreciate that the optimal demand response is highly time and location-specific. If future demand is to be integrated to support efficient network operation and development, an appropriate infrastructure is required to facilitate real-time and location specific demand response. Smart meters with advanced real-time functionality and appropriate communication systems will be essential for facilitating the change in network control paradigm required to support efficient investment in future network reinforcements. Less refined ‘restricted hour’ ToU tariffs would fail to deliver the optimum management of peak demand at the very local level, particularly due the potential lack of diversity and ‘lumpiness’ of load associated with electric vehicles and heat pumps. Not recognising the specifics conditions on individual LV feeder sections driven by actual locations of loads could compromise the potential for avoided network reinforcement costs.

6.16 Table 6-4 (NPV value of Smart) in effect defines the budget for changing the network control paradigm from passive to active. Optimising demand response would be accompanied with the investment in advanced smart metering functionality and appropriate communication infrastructure, and in this context, this work contributes to establishing a business case for a Smart distribution network.

7 Conclusions and further work

- 7.1 This study has been conducted in collaboration with the Energy Networks Association in order to inform the current GB Smart Meter Implementation Programme as to the required functionality of smart meters and the corresponding requirements on the associated communication infrastructure. The overall aim of the investigation has been to assess the potential benefits of a real-time distribution network control paradigm that incorporates real time demand response facilitated by a smart metering infrastructure. The estimated order of magnitude benefits, resulting from smart meter-enabled control of flexible demand, should inform the debate on smart meter functionality and communication infrastructure, and provide insights into the overall costs and benefits of different approaches to the implementation of smart metering.
- 7.2 This analysis is carried out in the context of the challenges associated with the future GB electricity system and, in particular, related to the electrification of the heat and transport sectors. One of the key concerns with the future GB low carbon electricity system is that, in the absence of a smart meter enabled real-time distribution network control capability, it will be characterised by much lower generation and network asset utilisation factors given: (i) a significant penetration of low capacity value wind generation combined with: (ii) a potential increase in peak demand that is disproportionately higher than the increase in energy. However both the transport and heat sectors are characterised by a significant inherent storage capability and this opens up unprecedented opportunities for optimising demand side response to enhance the efficiency of the entire end-to-end electricity supply chain, including electricity generation, transmission and distribution.
- 7.3 This work has quantified the order of magnitude impact on the UK electricity distribution network of electrifying the transport and heat sectors under both an unconstrained network control paradigm and an active network control approach based on optimised demand side response. Very significant opportunities for optimising demand response in relation to network constraints have been identified. The analysis shows that the value in NPV terms of changing the network control paradigm ranges between approximately £0.5bn and £10bn across the scenarios considered¹¹. This potential saving effectively defines the allowable budget for changing the network control paradigm from passive to active and, in this context, the study can inform the development of a business case for advanced metering functionality.
- 7.4 Future research in this area will focus on overcoming some of the limitations in the modelling approach used in this study. It is important to emphasise that this analysis is based on diversified household load profiles and (historical) average national driving patterns applied to all local networks. However significant deviations would be expected in individual circumstances and it has, for example, been shown that the impact of specific driving patterns may be very significant. Furthermore, these load patterns would vary significantly in

¹¹ We have also conducted a number of sensitivity studies to test the robustness of our conclusions. For example, in the event of a very low uptake of electric vehicles by 2030 of 10% with no uptake of heat pumps, the NPV benefits of changing the network operation philosophy would still be significant, approximately in the range between £0.25bn and £1bn.

magnitude, location and across time, which could have very considerable effects on the load and voltage profiles of local LV networks in particular. Recognising the specific conditions on individual LV feeder sections, driven by actual behaviour of time-varying loads in specific locations, will be critical for enhancing the utilisation of the existing assets and avoiding network reinforcements. Given that this analysis is based on fixed average load patterns, and it does not capture the variability of particularly lumpy loads, the benefits of active network control are underestimated. In addition, the application of hourly time resolution and assuming fully balanced loading condition in LV networks, will also result in the benefits being undervalued.

- 7.5 Future work will also include refining of the resolution of driving patterns both with respect to time and location, and a more detailed assessment of the impact of different types of heat pumps, taking account of different levels of house insulation, various arrangements for backup heating (electricity or gas based peak heat supply) and the application of alternative forms of heat storage under different critical outdoor temperature profiles. Also, the range of representative networks will be expanded to account for situations when there may be significant deviations from the impact quantified on the considered samples. Given that voltage constraints were demonstrated to be a significant network reinforcement driver, we intend to refine network reinforcement strategies and explore the feasibility of allowing a wider variation in LV system voltage in terms of both appliance compatibility and overall energy efficiency. These highlighted issues, albeit not sufficient to fundamentally change the conclusions of this report, will nevertheless be used to steer future efforts towards further enhancing the analysis in this report.
- 7.6 On the other hand, there will be a spectrum of other potentially significant benefits of advanced smart metering functionality and enhanced communication infrastructure that have not been considered in this study, but are recommended for further investigation. These include: benefits from reduced generation capacity requirements, provision of flexibility and contribution to national and regional system balancing and enhanced utilisation of the transmission network; improved outage management and better investment optimisation; and greater capacity to accommodate low-carbon generation and load growth. Moreover, the ability to influence responsive demand in real time through smart meters will have the potential to: increase the ability of the system to accommodate a range of future energy scenarios; incorporate vehicle-to-grid applications; and enable DNOs to contribute to the national demand-supply residual balancing function and hence improve real-time management of the GB transmission system. Some of these benefits are currently being investigated in more detail.
- 7.7 This work does not consider distribution network asset replacements that may have to be carried out due to aging of equipment, as major renewals of HV and LV underground cable infrastructure due to condition degradation over the period to 2030 are not currently envisaged. Furthermore, the increase in network utilisation, which would be achieved through an active control philosophy, would lead to an increase in distribution network losses, particularly for higher levels of penetration of EVs and HPs. However, the estimated NPV of the increased losses over the period under consideration is demonstrated not to be material. Moreover, the potentially significant impact of a large-scale penetration of small sized distributed generation together with more efficient use of energy have the potential to

release network capacity that could be used to accommodate some of the anticipated increase in demand, and these effects will be explored in future studies.

- 7.8 Clearly, very significant opportunities for optimising demand response in relation to network loading have been identified and quantified. It is very important however to appreciate that the optimal demand response will be highly time and location-specific. Theoretically, an optimal time scheduling of individual household loads, specific to each individual location, could be determined for pre-specified user requirements. Assuming that these requirements at each individual location are fixed in time (fixed EV charging requirements and patterns, fixed Smart Appliances and HP operating patterns), such an objective of optimal scheduling could be hypothetically achieved through a location-specific (at the household level) time of use tariff. However, all these loads will, very frequently and very significantly, deviate from any pre-specified schedule. Demand response will therefore need to be re-optimised for the actual situation arising; otherwise such deviations will potentially lead to LV network overloads and/or voltage profiles breaching statutory limits, given the lack of diversity and 'lumpiness' of loads associated with electric vehicles and heat pumps. The instantaneous increase in load caused by the simultaneous charging of an electric vehicle and operation of a heat pump (for example on returning home) can be in excess of 10kW per household which is indeed very significant. Only real time demand response optimisation, specific to changing user requirements and network constraints, can fully deliver the potential savings from enhanced asset utilisation and reduced network reinforcement. Smart meters with advanced real-time functionality and appropriate communication systems will be essential for facilitating the optimisation of demand response and the required change in the network control paradigm to support efficient network utilisation and minimise the requirement for investment in future network reinforcement. Such a change will require investment: in advanced smart meter functionality; in the communication infrastructure required to support real time network control; and possibly in the enhancement of distribution management systems.
- 7.9 Real time network control that incorporates demand response will also have significant implications on the UK regulatory and commercial arrangements as maintaining the present structure where supply and network businesses act independently will lead to inefficient network investment. Establishment of a Distribution System Operator type function, together with appropriate distribution network access and energy pricing structures, may need to be developed to facilitate both efficient real time network operation and efficient investment in future network reinforcement.
- 7.10 Notwithstanding the further opportunities identified for more refined analyses, the analyses undertaken as part of this study have clearly illustrated (and quantified) the benefits to customers (ultimately reflected in terms of avoided electricity charges) of adopting an active network control approach based on optimised demand side response enabled by smart metering functionality and an enhanced communication infrastructure. Moreover (with particular reference to Figures 5.7, 5.8 and 5.9) this report has clearly illustrated that, at overall penetration levels of up to 50%, the relative benefits of a Smart control paradigm over the BaU paradigm is particularly acute. It therefore follows that the benefits of a Smart approach will be significantly front-loaded under any ultimate EV and HP penetration scenario. In particular it points to a need to adopt a Smart approach from the outset and

hence, in the context of the proposed GB Smart Meter Implementation Programme, a compelling case to develop a smart metering and communications functional specification that will enable the required paradigm to be realised. It is worth mentioning that overseas smart metering programmes, to the best of our knowledge, are designed to facilitate real time demand response and the required paradigm change in distribution network operation.

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