INVESTIGATION OF THE IMPACT OF ELECTRIFYING TRANSPORT AND HEAT SECTORS ON THE UK DISTRIBUTION NETWORKS

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ABSTRACT

The work in this paper is conducted in collaboration with the Energy Networks Association to inform the current UK 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.

INTRODUCTION

The UK electricity system faces challenges of unprecedented proportions. By 2020, according to the Government Renewable Energy Strategy, 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) [1]. 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].

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 [3].

In this context, the analysis presented here 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.

Given that future costs of distribution network reinforcement will be driven by the network control paradigm, this work contrasts two approaches. First, the “Business as Usual (BaU)” approach where the distribution network is designed to accommodate any reasonably expected demand; and second, the “Smart” approach to optimise responsive demand at the local level in order to manage network constraints and avoid or postpone network reinforcements.

MODELLING OF DEMAND OF ELECTRIC VEHICLES

Electric vehicles (EVs) 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. For the purpose of this study, a detailed National Transport Survey (NTS) database is used [4]. 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.

On the basis of the records, approximately 67.4 million journeys are undertaken daily on average, by around 34.2 million vehicles. 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 [5]-[6], an average energy consumption of 0.15 kWh/km 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. Based on the available literature, in this exercise the central case model adopts 6 kW as the maximum power for charging EV batteries.

MODELLING OF DOMESTIC ELECTRIC HEAT PUMPS

Heat sector is another area that has significant potential for decarbonisation. The data associated with the operation of heat pumps (HPs) used in this work has been derived from empirical studies and field trials of micro-CHP and boiler systems conducted by the Carbon Trust. Figure 1 presents the electricity demand profile of an individual heat pump, mimicking the operation of a boiler or a micro CHP. The Figure also presents the aggregate demand of the operation of 21 different HPs in 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. The analysis is carried out under the assumption of achieving Grade A insulation levels in dwellings heated by HPs.

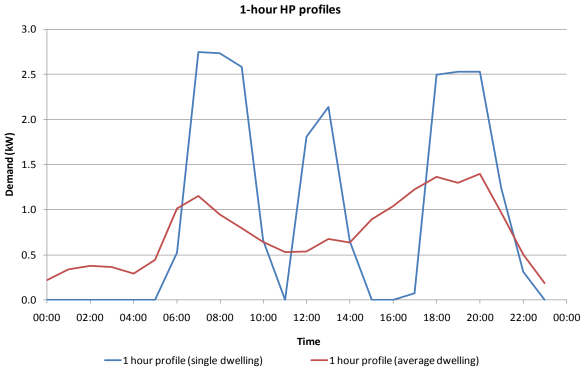

Figure 1: Demand profile of a heat pump following the operating pattern of a boiler and aggregate profile of HPs of 21 dwellings in hourly resolution

This work considered heat pump-based systems accompanied with thermal storage. The analysis shows that heat storage of the capacity of less than 25% of daily heat demand would be sufficient for flattening the 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.

OPTIMISATION OF RESPONSIVE DEMAND

Figure 2 shows a typical cold winter demand profile at the national level with (Smart) and without (BaU) the combined optimisation of EV and HP. Coordinated management of responsive demand makes it possible to significantly reduce system peaks. In the BaU case, 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 double, experiencing a 92% increase (out of which 36% can be attributed to EVs, and 56% to HPs). In a jointly optimised case the peak increase is only 29%. This clearly has a very profound impact on the utilisation of generation and network capacity in the electricity system.

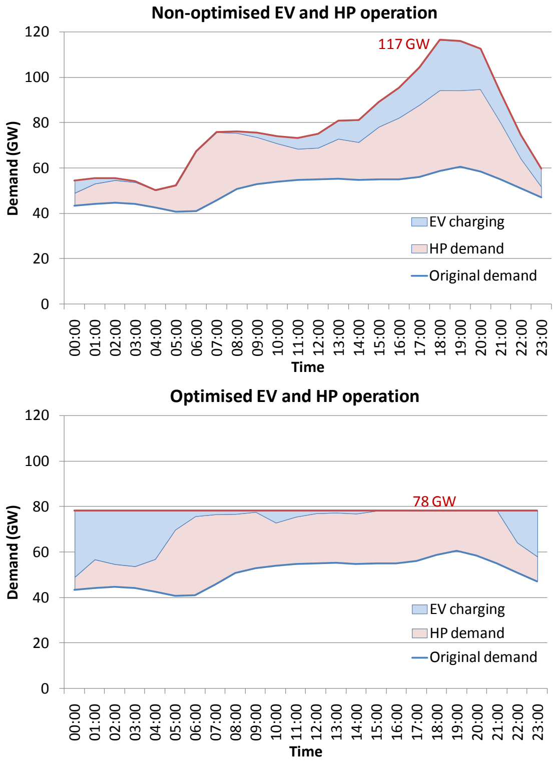

Figure 2: EV charging and HP operation in BaU (upper) and Smart (lower) cases

CASE STUDY

To study the network impacts of the two approaches, representative high voltage (HV) and low voltage (LV) radial distribution networks have been created [7]-[8]. Three LV representative networks used in the study represent a city/town area with a load density of 8 MVA/km^2, a semi-urban/rural network with a 2 MVA/km^2 load density and a rural network with a load density of 0.5 MVA/km^2. The HV network model used in this investigation is derived from a modified network topology of Coventry. 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.

The design of the representative LV and HV network follows the principles of Engineering Recommendation P2/6 [9]. Networks are designed as meshed but operated as radial, with an appropriate number of normally open points. The designed networks comprised the equipment taken from the set of standard ratings of transformers and underground / overhead lines, satisfying at the same time fault level and voltage limit constraints. AC load flow studies have been based on hourly winter and summer workday load profiles for the domestic sector.

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 [10], although it should be noted that the benefits of cyclic rating reduce with flattening of the demand profile.

It is important to mention that the analysis carried out in this work is based on diversified household load profiles and (historical) average national driving patterns applied to all local networks. However, significant deviations could be expected in specific circumstances, such as when vehicle driving patterns significantly deviate from the average. 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.

Evaluating the impact on LV and HV networks

Figure 3 and Figure 4 present the percentage of overloaded distribution transformers and percentage of reinforced LV feeder length in 2 MVA/km^2 representative network under passive and active network control philosophies, for four different levels of penetration of EVs and HPs.

As expected, with increasing penetration of EVs and HPs the percentage of overloaded distribution transformers also increases. Furthermore, it can be observed 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 approaches is larger for 25% and 50% penetration levels then 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. Similarly, Figure 4 clearly shows that passive distribution network operation regime (BaU) will require significantly higher proportion of LV feeder section reinforcement than the active approach (Smart).

The three representative LV networks were used to populate the HV network model. Figure 5 and Figure 6 present the percentages of overloaded primary transformers (33/11 kV) and the percentages of length of HV feeders that would need to be replaced to eliminate thermal and/or voltage drop violations under passive and active network control philosophies. 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.

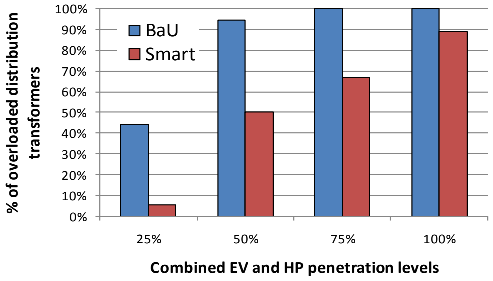

Figure 3: Percentage of overloaded distribution transformers

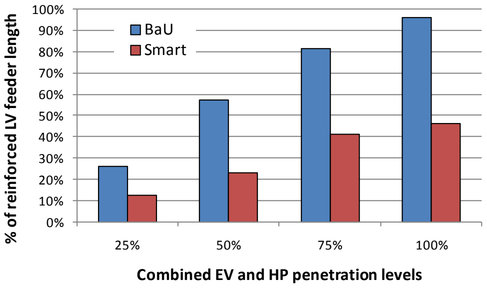

Figure 4: Percentage of reinforced LV feeder length

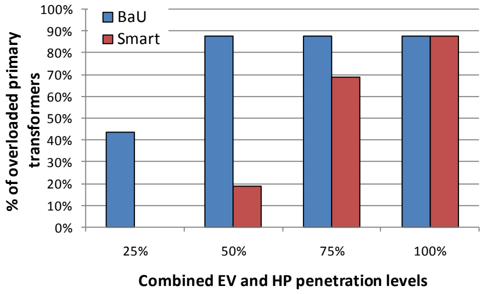

Figure 5: Percentage of overloaded primary transformers

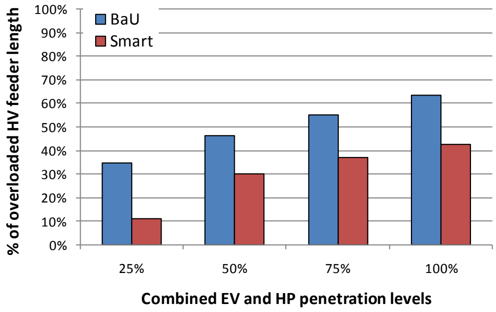

Figure 6: Percentage of overloaded HV feeder length

In order to deal with overloads of feeders and transformers and inadequate network voltages caused by the uptake of transport and heat demand, analyses have been conducted both for a like-with-like network replacement strategy and for a strategy based on splitting LV network by inserting new distribution substations. 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 would indicate a lower boundary of the value of smart meter-enabled active network management capability.

Quantification of active network control benefits

The Net Present Value (NPV) of the smart meter enabled active control of GB distribution networks has been evaluated for a range of 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 [11]), while the costs of distribution network equipment (feeders and transformers) are taken from the DPCR5 Final Proposals [12]. Five scenarios with different levels of penetration of EVs and HPs have been considered as shown in Figure 7. This is consistent with the Government-projected cumulative penetration of 1.7 million cars by 2020 (approximately 5% penetration) [2]. Starting from year 2020 to 2030, scenarios 1 to 5 represent different levels of uptake of EV and HP. Table 1 summarises the NPV-based value of Smart management of demand, enabled by an appropriately specified smart metering system, for the entire GB distribution network. This value ranges between £0.5bn and £10bn, across all scenarios considered.

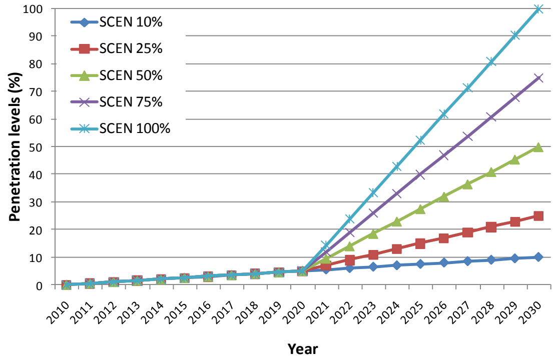

Figure 7: Penetration scenarios for combined EVs and HPs

Table 1: 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%	0.8 - 2.5	0.3 - 1.0	0.06 - 0.2	0.03 - 0.08	0.5 - 1.6
SCEN 25%	1.9 - 6.3	0.7 - 2.3	0.2 - 0.7	0.04 - 0.13	1.4 - 4.5
SCEN 50%	3.8 - 12.4	1.5 - 4.9	0.3 - 1.0	0.13 - 0.42	2.5 - 8.1
SCEN 75%	5.1 - 16.7	2.5 - 8.1	0.3 - 1.1	0.22 - 0.71	2.7 - 9.0
SCEN 100%	5.9 - 19.3	2.9 - 9.6	0.4 - 1.2	0.26 - 0.85	3.1 - 10.0

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 analysis has shown that the estimated NPV of the increased cost of losses over the period under consideration would not be significant.

CONCLUSIONS

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 have been identified for optimising the demand response to address network constraints. The analysis shows that the value in NPV terms of changing the network control paradigm ranges between £0.5bn and £10bn across the 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 paradigm.

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