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The Large Scale Roll-Out of Electric
Vehicles: The Effect on the Electricity
Sector and CO2 Emissions

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Tooraj Jamasb*

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Keywords Electric Vehicles, CO2 Emissions, Electricity Demand Management

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The UK government has set the ambitious targets of 20 and 50% reduction in greenhouse gas emissions by 2020 and 2050 respectively. The transport sector accounts for 21% of total CO₂ emissions in the UK and can, therefore, be important for achieving the emissions reduction targets. Within the transport sector, electric vehicles (EV) are considered as one of the important mitigation options. However the effect of EVs on emissions and the electricity sector is subject to debate. We use scenario analysis to investigate the emission reduction potential of EVs and their interaction with electricity sector. We show that managing the charging patterns could reduce adverse effects of EVs on the electricity sector while the number of EVs remains the factor affecting the mitigation potential. Our findings indicate that in the UK, by 2030, EVs could result in up to 32% emissions reduction compared to advanced internal combustion engines. We also found that the need for new electricity generation and distribution capacity to meet the conventional electricity demand and demand from EVs could be reduced by up to 12% from 70.6 to 61.8 GW if the EV's electricity demand is managed.

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1. Introduction

The UK government has set ambitious targets of 20 and 50% reduction in greenhouse gas (GHG) emissions by 2020 and 2050 respectively (DECC, 2008). The transport sector accounts for 21% of total CO₂ emissions in the UK and can, therefore, be important for achieving the emissions reduction targets (DECC, 2009c). Among other alternative fuel options such as biofuel derived vehicles, different types of electric vehicles (EVs) such as Battery Electric Vehicles (BEV), Hybrid Electric Vehicles (HEV) and Plug in Hybrid Electric Vehicles (PHEV) can play a role in emissions reduction in the transport sector (CCC, 2009b). However, it is also important to assess the effect of large-scale roll out of the EVs on the electricity generation and networks.

The average annual utilization of the UK electricity generation capacity is below 55%¹ (Strbac, 2008). In the absence of demand-side management (DSM) measures, a large-scale roll out of BEVs/PHEVs (EVs)² can reduce this figure and therefore the overall efficiency of the electricity sector. This is because if the EVs are charged at peak hours, it leads to a higher peak electricity demand (with the same valley floor). Also, long recharging time of EVs (i.e. 10 Hours for full recharging of a typical fully depleted battery)³, including charging at peak hours, could require a larger generation capacity. This in turn would lead to a need for a larger reserve margin in generation (Hadley and Tsvetkova, 2009; Perujo and Ciuffo, 2010). Where the system operates close to capacity, a large scale roll out of EVs might further strain the supply system

¹ The average plant load factor of the operating power plants in the UK is less than 55%.

² Throughout the paper, EVs refers to both BEVs and PHEVs unless otherwise stated (See Section 2.1 for justification).

³ Charging times between 2.5 to 13 hours are reported for different car models (Gigaom.com, 2010). In this study we consider a charging time of 10 hours for a typical vehicle (MacKay, 2009; Stephan and Sullivan, 2008).

unless the electricity demand from EVs are managed and shifted to off-peak hours (BERR and DfT, 2008).

If the demand for charging is managed and shifted to off-peak periods, the existing generation and network capacity are not only expected to be sufficient for the extra demand from EVs' (BERR and DfT, 2008; Elementenergy, 2009; RAE, 2010), it could also increase the capacity factor of the existing system and improve the efficiency of system accordingly.

In general, the fuel economy (defined as conversion efficiency of the input energy to the power at wheels) of Electric Motors is higher than those of Internal Combustion Engines (ICEs) (Offer et al., 2010; Campanari et al., 2009; Armand and Tarascon, 2008; Thomas, 2009). In other words, electric motors are more efficient than ICEs. In terms of emissions, the main source of emissions for ICEs and EVs (for PHEVs when operating on electricity) is their fuel which is direct for the former and indirect (emissions from electricity generation) for the latter.⁴

In the UK, based on average emissions factors for electricity generation proposed by DEFRA (2009)⁵, the well to wheel emissions from a typical BEV amounts to 69 gCO₂/km compared to 172 and 156 gCO₂/km from petrol and diesel sources respectively (BERR and DfT, 2008). McCarthy and Yang (2010) in a study of the US reason that, for short and mid term analysis (i.e. for a life time of a power plant, 30-40 years), using emissions from marginal power plants instead of average emissions for electricity generation is more suitable for calculating the mitigation potential of EVs.

⁴ A more accurate approach to compare carbon efficiency of ICEs and EVs, is to use lifecycle analysis (see Samaras and Meisterling, 2008; Sioshansi and Denholm, 2009; Stephan and Sullivan, 2008). In this study we focus on operating emissions of ICEs and EVs.

⁵ Department for Environment, Food, and Rural Affairs (DEFRA).

This stems from the view that in the short term EVs are not a part of the conventional electricity demand and they can be regarded as an additional source of demand. In other words, considering that the current electricity system is developed to meet the conventional demand, the additional demand from EVs is provided by generation plants which otherwise would not have been in use. Therefore, when calculating the emissions from EVs, it is realistic to consider emissions from marginal power plants. However, in the long run, as EVs gradually become a major part of the transport sector, they will constitute an integrated part of electricity demand. In this case, the EVs' demand for electricity would become part of the planning and development of the electricity sector, and average emission measures would be applicable.

The present study aims to explore the effect of large-scale roll out of EVs (BEVs/PHEVs) on the electricity sector and evaluate the mitigation potential of EVs in order to address the uncertainties in both areas.

The next section presents the analytical approach and the assumptions used in this study. The results for the effects of EVs on electricity sector and mitigation potential of EVs are examined and discussed in Section 3. Sensitivity analysis of the results is discussed in Section 4 and conclusions are presented in Section 5.

2. Methodology

When assessing the impact of EVs on the electricity sector and CO₂ emissions the following factors should be considered: (1) technological performance of the vehicles (kWh/km), (2) number of EVs entering the fleet, (3) emissions intensity of electricity generation (Kg CO₂/kWh), and (4) the charging pattern of the EVs.

2.1. Vehicle Performance

In terms of energy efficiency, we assume that BEVs and PHEVs (when driven on electricity), have comparable energy consumption. For this, we consider that the extra weight of the internal combustion engine (ICE) in a PHEV is comparable with the extended weight of the extended range battery in a BEV. Therefore, we assume that when in electric mode, as the weight of the ICE (in PHEV) is compensated by the extra weight of battery (in a BEV), the fuel economy of both technologies are comparable (Stephan and Sullivan, 2008). Besides, as PHEVs are expected to offer most advantage in short distance commuting trips⁶, we assume that the early adopters are among those who will use their PHEVs for short distances and therefore always running on electricity. Therefore, we assume that BEVs and PHEVs (when driving on electricity) have similar charging behaviour. Fuel economies of 0.26 and 0.2 kWh/km are reported for 2003 and 2009 for BEV/PHEV (driving on electric mode) technologies by Stephan and Sullivan (2008) and Element Energy (2009) respectively. We also assume that both BEVs and PHEVs (60)⁷ could run on electricity for 100 km (BERR and DfT, 2008).⁸

2.2. Number of EVs

In the present study, we use the forecasts of the number of EVs (both BEVs and PHEVs) as suggested by BERR⁹ and DfT (2008). Table 1 summarizes the estimated number of BEVs and PHEVs used in our scenarios. The table presents the results of

⁶ Assuming a 100 km range for BEVs and PHEVs (60), almost 60% of all UK vehicle-km can be undertaken by EVs (see Figure 2).

⁷ PHEV 60, is a Plug in Hybrid Electric Vehicle which can go 60 miles (\approx 97 km) on electricity.

⁸ About 90% of participants in a survey reported in Element Energy (2009) were considering using EVs for ranges of up to 60 miles. Therefore, for this range BEVs and PHEVs are assumed to be comparable. For more information about the survey see Section 3.

⁹ Department for Business Enterprise, and Regulatory Reform (BERR).

the scenario analysis by BERR and DfT (2008). The actual number of EVs (BEVs and PHEVs) in the fleet in 2011 was 1017 which is 75% and 80% less than the predicted numbers for 2010 in the BAU and HR scenarios respectively. However, the increase in the number of EVs from 2010 (167) to 2011 (1017) is substantial (an increase of more than 6 times). The official prediction is that by fully implementing the so called "plugged-in car grant" scheme and with the increase in the variety of car models whose characteristics are more compatible with the requirements of the scheme, reaching the predefined number of electric vehicles in the fleet is achievable (Vaughan, 2011). As evidence, the effects of the "plugged-in car grant" scheme are found to be substantial. For example, from 30 June 2012 to mid-September 2012, 1706 claims were made through the scheme (DfT, 2012). Therefore, the figures in Table 1 (for 2020 and 2030) are considered in the present study. Several assumptions are used in car uptake scenarios in BERR and DfT (2008) and the most important ones are presented in Table 2.

Table 1: Estimated uptake of EVs and PHEVs
Source: BERR and DfT (2008)

	2010		2020		2030	
Scenario	BEV	PHEV	BEV	PHEV	BEV	PHEV
BAU	3,000	1,000	70,000	200,000	500,000	2,500,000
HR	4,000	1,000	1,200,000	350,000	3,300,000	7,900,000

In BERR and DfT (2008) the rate of EV uptake is assumed to be non-linear during the period of the study. More precisely, according to BAU and HR scenarios, in 2020 the share of EVs (BEV and PHEV) in the fleet is expected to be less than 1% and less than 5% of the total cars in the fleet respectively. In the BAU scenario, the share of

EVs among all the new cars entering the fleet is 3% in 2022 and 21% in 2030. In the HR scenario, the figures are 7, 34, and 53% in 2016, 2024, and 2030 respectively.

Table 2: Assumptions Used for Developing EV Uptake Scenarios
Source: BERR and DfT (2008)

	Unit	BAU		HR	
		2010	2030	2010	2030
Total Number of Cars on the fleet	Million	≈ 29	≈ 35	≈ 29	≈ 35
Share of EVs (BEV & PHEV) among all the cars on the fleet	% of all cars in the fleet	≈0	8	≈0	32
Share of EVs (BEVs & PHEV) among new cars entering the fleet	% of cars entering the fleet	≈0	21	≈0	53
Area of penetration	-	London area		Beyond urban areas	
Car parks being able to connect to grid	% of total	-	-	4.9% in 2020	32% in 2030

For the HR scenario, it is also assumed that after 2014 the limitation on the variety of existing EV models would start diminishing and in 2020, this would not be a major problem for EV uptake any more. In terms of price, it was assumed that after 2020 the price of EVs would decrease significantly. In addition it is considered that EVs (BEVs and PHEVs) would be treated as “super credits” under market schemes such as zero tailpipe emissions vehicles. It is also assumed that in addition to the UK, such regulatory and incentives should be in place in other European countries as it will be uneconomic for manufactures to produce cars only suitable for one market.

2.3. Carbon Intensity of Electricity Generation

As mentioned earlier, in the short to mid-term, it is realistic to consider marginal plants as the source of electricity for EVs (McCarthy and Yang 2010). In this study we use the estimates of hourly CO₂ intensity of electricity generation from marginal

plants in 2030 prepared for the Committee on Climate Change (see Element Energy, 2009). However, it is noteworthy that on occasions such as in cold winters when the consumption of natural gas in the residential sector increases considerably, coal could replace natural gas as the marginal source (NG, 2010b) and emissions from marginal powerplants could, therefore, increase.

We assume that the carbon intensity of the grid decreases by 10% in each decade due to the penetration of the state of the art technologies. Based on this assumption, we estimated the hourly CO₂ emission factors for marginal plants for 2010, 2020. The results are shown in Figure 1. For verification, we compared the calculated data with the historical and existing data. Natural gas turbine power plant is the marginal plant in the UK any time except offpeak hours (i.e. between 7:00 and 24:00) and depending on the technology, the emission factor from such a plant is between 350 and 450 g/kWh. Our calculations (for 2010) are in line with the CO₂ emission factor of a typical gas turbine power plant operating in the UK in 2010.

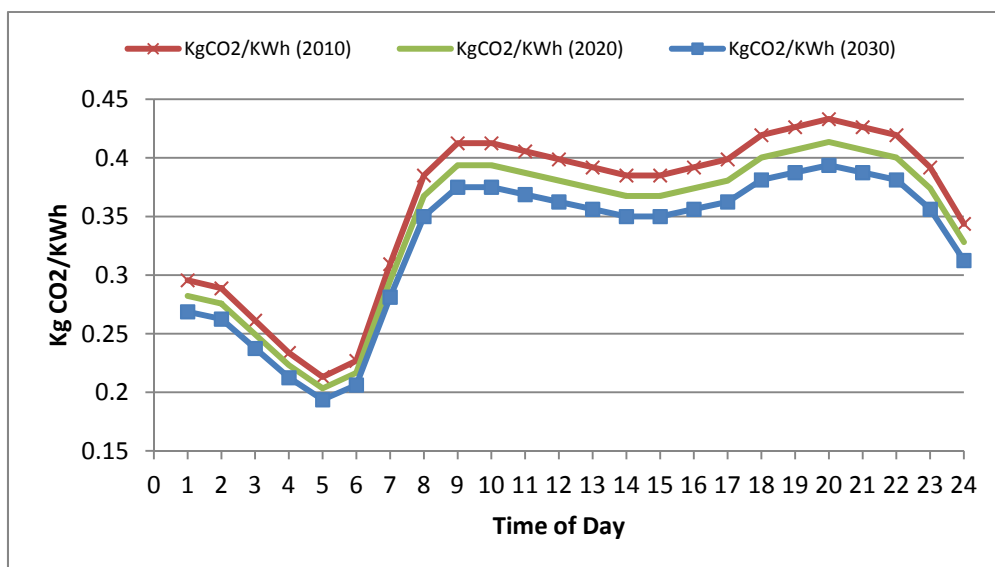


Figure 1: Hourly CO₂ emissions factors from marginal power plants (Kg CO₂/kWh)

During off-peak hours (i.e. 00:00-7:00) as shown in Figure 1, CO₂ emissions from marginal power plants are much less than non off-peak hours. The reasoning behind this is the merit order of power plants in the UK. In 2005 in the UK, the merit order of dispatch were as following: industrial CHP, biomass power plant, nuclear, imported electricity, coal steam turbine, heavy fuel oil steam turbine and natural gas combined cycle (Vuorinen, 2007). In 2007, nuclear and renewable were the main sources which were used to generate up to 17 GW and 20 GW electricity in a typical winter day and summer day respectively and this would justify the low emission factors of the marginal plant during off-peak hours.

2.4. Charging Pattern of EVs

In order to explore the importance of charging behaviour for the electricity system and CO₂ emissions, some charging patterns are developed in this study and are further applied in our scenario analysis. In a survey prepared for the Committee on Climate Change, the expectations of early adopters and the necessary infrastructure required to meet their needs were explored through questionnaires from a sample of household and commercial consumers (Elementenergy, 2009). The participants in the survey were asked about their recharging behaviour, daily mileage, and possible recharging locations. We use these survey results to design charging scenarios and analysis of the effects of charging patterns of EVs. Given these assumptions the following subsections outline a set of charging scenarios.

2.4.1. General assumptions for charging patterns

As the EVs need regular recharging, at an aggregate level, the travel behaviour of the users in terms of trips terminating at charging place and the distance they travel prior to that influence their recharging patterns. For our scenario analysis, we use the estimates provided by the Department for Transport (DfT, 2007b). Figures 2 and 3 show the estimated percentage of car trips terminating at home at different time periods during a day and their daily travel distances respectively.

Because of the lack of data, it is not possible to know how many of the trips shown in Figure 2 are the last trips of the day. However, when combining the data from Figures 2 and 3 and assuming that individuals start charging their BEVs as soon as they reach home (for home charging scenario), the data could be used for predicting the charging behaviour of individuals. More precisely, it is assumed that distances travelled before reaching home are distributed evenly during the day (e.g. independent of the time at which the cars arrive home, 30% of the cars have driven less than 50km before reaching home). Based on this, we can assume that each trip which terminates at home is the last trip of the day.

We assume that the travel behaviour of individuals remain unchanged during the time period studied. This is a controversial assumption because the mode of transport which individuals use would vary even during a year. For example, during a cold winter day, it is expected that the number of individuals who use bicycle or public transport would be less than a summer day. In other words, during the winter, drivers use their cars more than in summertime which means less time during which cars are parked at home and more energy needed to recharge the car mainly because of the

long distances being driven before reaching home. However, for the present study, a typical day in the year is considered to represent the whole year and that travel behaviour is considered not to change during the period of the study.

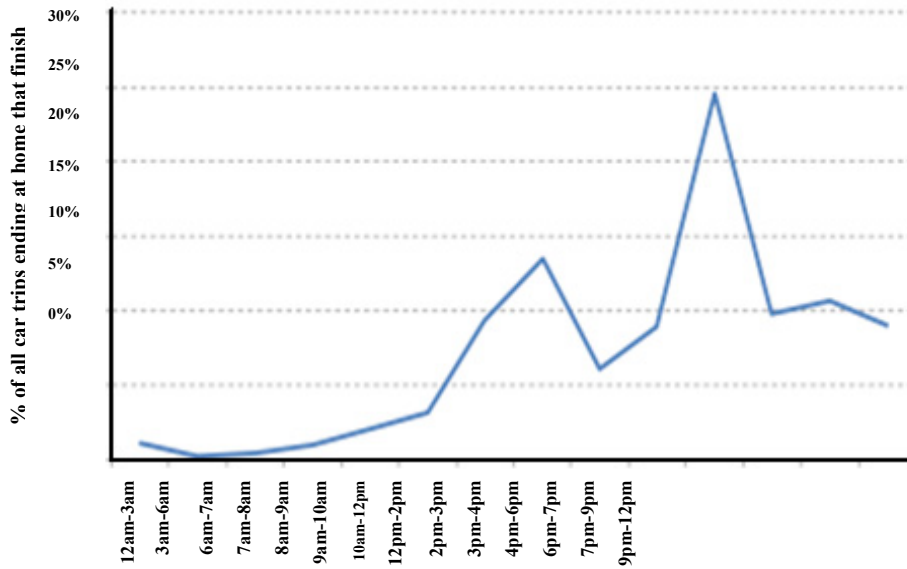


Figure 2: Car trips terminating at home
 Source: DfT (2007b)

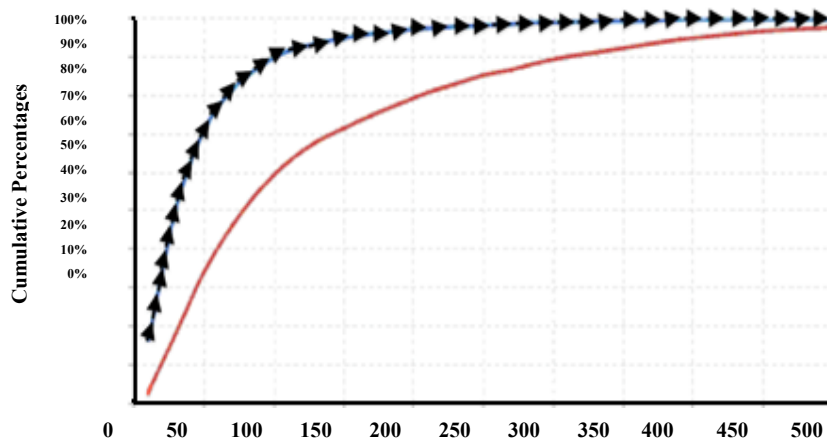


Figure 3: Daily distance travelled by private cars (km/day)
 Source: DfT (2007b)

We use a model based on the expected travel behaviour of drivers from DfT (2007b) to predict electricity demand patterns from EVs for a 24-hour period using a set of EV charging scenarios.¹⁰

2.4.2 Home-Based Charging Scenario

In the DfT (2007b) study, the average time during which the car is parked at different destinations (e.g. shopping centers, work, home, etc) are compared and homes are found to be the main place at which cars are parked most of the time during 24 hours (on average 7.1 hours). In addition, lack of work-charging, fast-charging etc, make early adopters willing to charge their cars at home. Based on these two facts, for developing the baseline-charging scenario, home charging is considered to be the dominant mode of charging for EVs.

In this study, home-based charging is defined as the charging mode which occurs during the time at which individuals are at home. During this time, the car can be parked at home private parking, on street or public parking. Charging is assumed to begin as soon as people arrive home and stop as soon as the battery is fully charged. The time distribution at which car trips terminate at home (Figure 1) is used to predict the charging pattern of EVs.

Given individuals' travel behaviour (Figure 2), the charging period needed for each vehicle is calculated based on the distance they travel before reaching home. For our calculation, it is assumed that each trip which terminates at home is the last trip of the day (see Section 2.4.1.). It is also assumed that distances travelled before reaching

¹⁰ The model was written using the computer programme Matlab.

home are distributed evenly during the day. For example, we assume that among the 25% of the cars that arrive home between 4:00 and 6:00 p.m. (Figure 1), 10% travelled below 25 km and 33% travelled below 50 km and so forth (Figure 2). Based on these two assumptions the time needed for charging the vehicle could be calculated.

Batteries are assumed to provide energy for up to 100 km of driving (BEV or PHEV 60), which assumed to be the representative of a typical current technology¹¹ (BERR and DfT, 2008). Therefore, if a car travels for 25 km, the time that it needs to be recharged is a quarter of the time needed for full charging of a completely depleted battery (MacKay, 2009; Stephan and Sullivan, 2008).

Considering a given point in time as base (e.g. 3:00 p.m.), the number of cars being plugged in is equal to the number of cars arriving home at that time. It is slightly different for the following hours. For example, at 4:00 p.m. the number of cars that are plugged in is equal to the number of cars arriving home at 4:00 p.m. plus the number of cars still plugged in from the previous periods. For instance, if 5% of cars arriving home at 3:00 p.m. have travelled less than 10 km (Figure 1), these vehicles will no longer be plugged-in at 4:00 p.m. because they would be fully charged before 4:00 p.m (calculated based on the assumption that 10 hours is needed to fully charge an empty battery). Hence, the number of cars being plugged in at 4:00 p.m. is equal to the number of cars that arrive home at 4:00 p.m. plus 95% of the cars that arrived home at 3:00 p.m. Equation (1) describes the above assumptions. Following the above

¹¹ Improvement in the charging technology during the time is not considered in this study.

methodology, the percentages of vehicles being plugged in at each point of time are shown in Figure 4 (home charging scenario).

Number of cars need electricity at time “t”	=	Number of cars plug in at “t”	+	Number of cars being plugged in at “t-1”	-	Number of cars fully charged between “t-1” and ”t”	(1)
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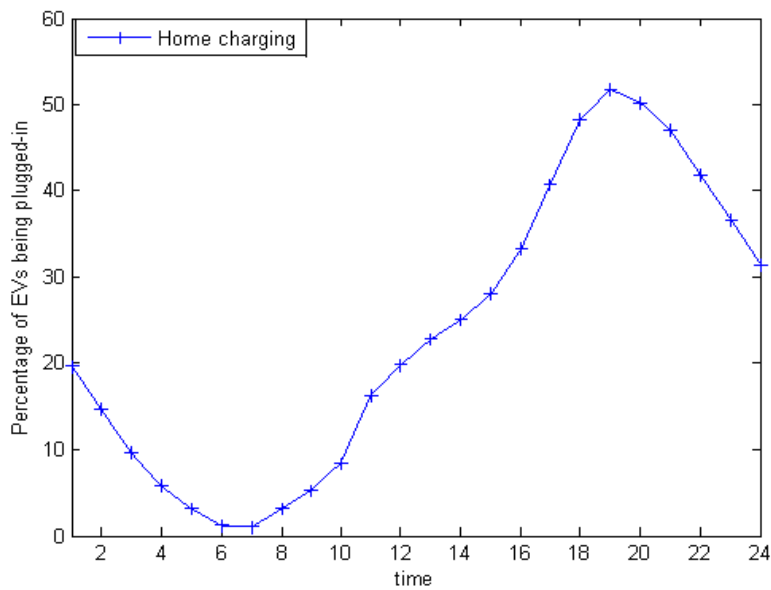


Figure 4: Home based charging scenario (% of EVs)

2.4.3 Workplace Charging

The results of the survey of EV users indicate that around 30% of the individual and more than 50% of commercial EV owners are willing to use workplace-charging facilities to recharge their electric cars if the facilities are available (Elementenergy, 2009). However, over time, some factors could affect the individuals’ willingness to use work place charging. Among other factors, improvement of battery technology, electricity pricing, and roll-out of charging infrastructure are considered to be the most important and are described briefly in Table 3.

Table 3: Factors Which Could Motivate Work Place Charging

Factor	Effects on individuals' willingness to use work-place charging
Improvement in battery technology	If batteries are charged faster than 10 hours ¹ , it will become more doable for individuals to have their car charged (to a reliable level. i.e. to a level sufficient for the return journey home) during 8 hours of working.
Electricity pricing	If incentives such as cheaper electricity at off-peak hours are in place, this could motivate individuals to charge their cars when they are at work (cheaper off-peak electricity) than when they are at home (more expensive peak electricity) ² .
Charging facilities	If reliable charging facilities/infrastructures are available at working area, individuals could make sure that they will have enough charge for their trip back home and use work-place charging as an alternative option to home charging.

¹ As discussed in Section 1, charging time in several models is less than 10 hours. However, 10 hours is considered as typical charging time needed for fully charging a depleted battery in this study.

² For relatively wealthy early adaptor, it is less probable that electricity pricing schemes result in major difference in work charging instead of home charging. However, it could have some minor impacts.

Considering the results of the survey, it could be argued that when workplace-charging facilities are available, up to 30% of individuals will charge their cars at work (i.e. between 9:00 a.m. and 5:00 p.m.) instead of charging at home. However, 30% is assumed to be the highest percentages of individuals who use work charging instead of home charging (and not using that as a complementary charging option). In other words, it is not accurate to say that 30% of individuals only use work-place charging as they might use both alternatives at the same time. Besides, to maximize the range of the travel (i.e. the maximum distance on electricity for a PHEV) individuals would probably use both alternatives (i.e. home and work charging). Therefore, to consider these uncertainties, a range between 10 and 30% shifting from home charging to work-place charging is considered in this study. Figure 5 shows the effect of the availability of workplace charging facility on charging patterns of the EVs.

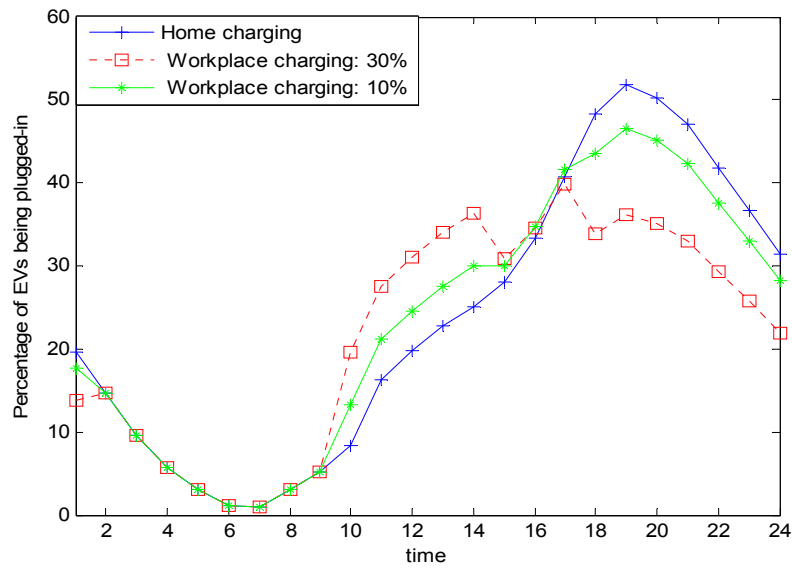


Figure 5: Workplace charging scenario

2.4.4. Fast Charging

Fast Charging is an option where EV owners are able to charge their cars in short periods of time (e.g. 15 minutes) using high voltage electricity in locations similar to conventional fuel stations (Think, 2010). Due to limited past experience, it is difficult to predict the impact of availability of fast charging facilities on individuals' charging behaviour.

The results of the user survey (Element Energy, 2009) indicate that fast charging and workplace charging lead to the same utility for both EV owners and those who are considering buying EVs. Utility is defined as reliability of different charging options and ease of using them. Given this similarity, we assume that fast charging could reduce the demand for home charging by up to the maximum level of 30% (similar to workplace charging). In addition to analyse the effects of fast charging on demand for home charging, we use the following assumptions for the EVs' charging demand in this scenario:

- Based on the UK national travel survey almost 50% of the total trips are commuting, businesses and educational trips (DFT, 2009). Therefore it is assumed that in case of availability of fast charging, these individuals would charge their cars when they are on the way to (7:00 a.m. and 9:00 a.m.) or back from (9:00 a.m. and 5:00 p.m.) work or study.
- The other 50% of the trips are those for leisure, visiting friends and shopping (DFT, 2009). Since there is not a specific time for such trips, it is assumed that these trips are distributed evenly during the day and consequently the time at which individuals start charging their cars are also considered to be distributed during the day.

The results of assuming 10 and 30% reduction in home charging due to the use of fast charging are shown in Figure 6.

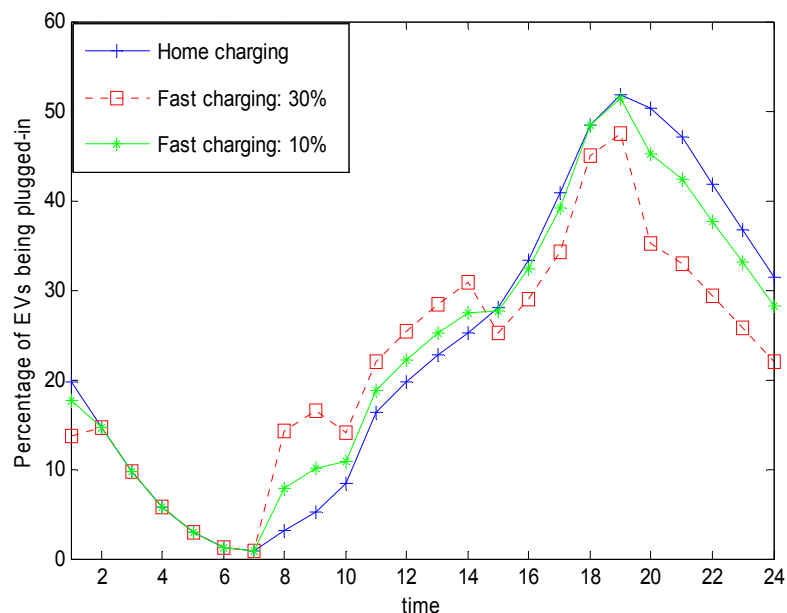


Figure 6: Fast charging scenario

2.4.5. Battery Exchange Stations

The concept of battery exchange stations is adopted from recent experience in the mobile phone industry through which all mobile producers agreed to use similar forms of chargers (ITU, 2009). Standardization of batteries could –but not necessarily will- promote schemes such as battery exchange station. This is because, different car models could use identical batteries and it is more practical to provide batteries to car owners in a typical battery swap station. In terms of convenience and the time needed for the consumers to have their batteries charged, battery exchange and fast charging schemes are comparable. Despite the similarities, the schemes are different in terms of attractiveness to consumers and the manner in which the schemes can shift the electricity demand from home-charging.

To our knowledge, there is no such a scheme exists in the UK to date and it is hard to predict the effectiveness of a battery exchange scheme in shifting the charging demand from home charging. Nevertheless, in an ideal scheme in which the car company owns the batteries (i.e. through leasing) and guarantees to provide fully charged batteries to consumers in return for an empty battery (considering the cost of charging in a predefined time e.g. for 5 years after the car is sold), battery exchange could be an attractive option for consumers for recharging their cars. The effectiveness of such a scheme could be higher than work-place charging because in terms of reliability and convenience, it is comparable to conventional petrol stations. Therefore, the upper limit for effectiveness of this scheme in shifting charging pattern from home charging is considered to be higher than that of work-place charging and considered to be 40%.

On the other hand, if the battery exchange scheme is not accompanied by an appropriate leasing scheme, issues such as battery degradation (decrease of the battery capacity due to chemical degradation of chemicals in the battery) and the possibility of receiving old batteries in return for a new one can make this scheme less attractive than fast charging and/or work-place charging. Therefore, the scheme's lower limit of effectiveness in shifting charging demand from home-charging is considered to be lower than other mentioned charging alternatives and considered to be limited to 5%.

Since the rationale behind businesses is to maximize profit, the owners of battery swap stations are expected to charge the batteries during the off-peak hours (23:00–7:00) when electricity is relatively cheaper. Although in real world, this could be traded off with inventory costs and energy-storage benefits to the grid, for simplicity, these are not considered in this study. Figure 7 shows the result of 5 and 40% reduction in home charging demand due to the introduction of battery exchange scheme with charging at off-peak hours.

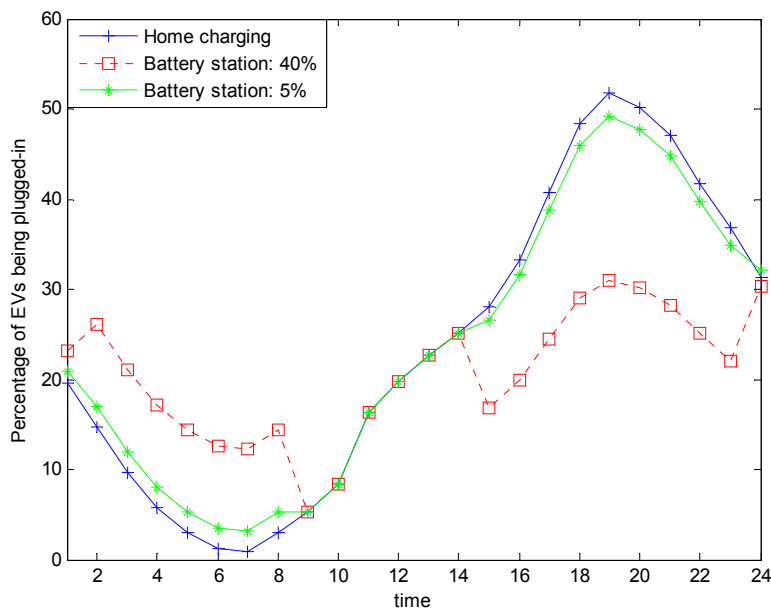


Figure 7: Battery exchange charging scenario

Although individuals arrive home at different time during the day, it does not necessarily affect the time of charging in the battery exchange scheme. More precisely, in the simplified model considered for the battery exchange scheme, it is assumed that the shop owner charges the battery during off peak hours and the consumer can just pick it up at the shop. However as discussed above, financial factors such as cost of inventory could motivate the shop owners charging the batteries during non-off-peak hours investigation of which is assumed to be beyond the scope of this study.

2.4.6. Battery Exchange and Fast Charging in Combination

Given the similarities between battery exchange and fast charging, some of the consumers attracted to these schemes would belong to the same group. In other words, these schemes would be interdependent and when assessing their effects, they could not be considered to be simply additional. However, implementation of one scheme might intensify the effects of the other. Therefore, the range for home charging reduction potential (for simultaneous implementation of these schemes) is assumed to be between 15 and 50%.

In other words, we assume that although some individuals prefer using either fast charging or battery swap schemes, there exist some individuals for whom both schemes would result in the same utility and will use either of the schemes depending on their availability. We assume that half of the reduction in demand for home charging would be distributed during the off-peak hours (following the battery

exchange scheme) and the rest would follow the same pattern as described in fast charging scheme. The results are shown in Figure 8.

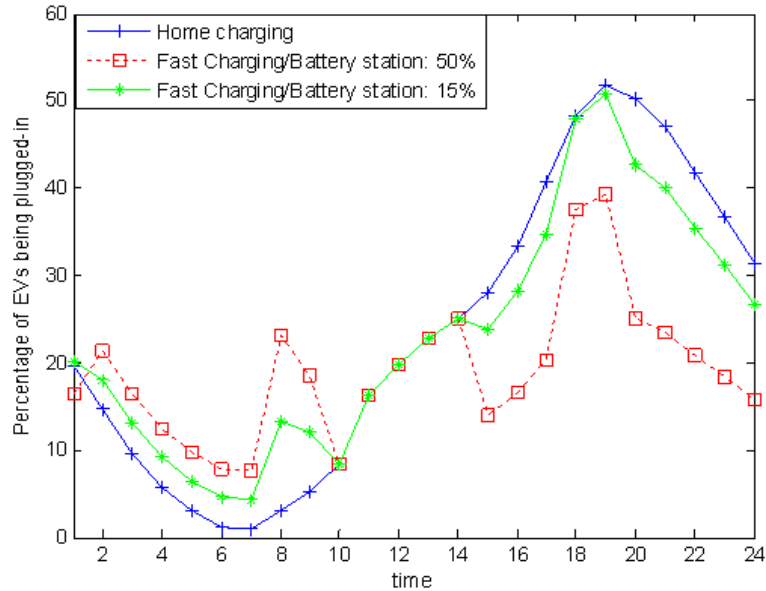


Figure 8: Battery Exchange/Fast Charging scenario

2.4.7. Conventional Electricity Demand Side Management (DSM)

Time of use pricing and real time pricing are two conventional schemes for electricity demand side management. These schemes aim to shift electricity demand to off-peak hours by using different prices on electricity depending on the time of use. The schemes are estimated to result in up to 5% reduction of conventional electricity demand at peak hours (Newsham and Bowker, 2010). Given the inherent differences between conventional and EVs' electricity demand, it is assumed that conventional DSM measures would be more effective in the context of EVs. This is due to the fact that some conventional electricity demand are either inelastic and/or are unlikely to be affected by differential pricing (e.g. refrigerator or lightning).

However, this is slightly different in the case of EVs. If users have sufficient time to charge their cars during the off peak hours they will probably do so. This would not reduce the individuals' utility, and it would also reduce their spending on electricity. This would be the case especially, if separate meters for EVs with different pricing rates (i.e. big difference in peak and off-peak prices of electricity for charging the car) are in place. In that case, the price difference of peak and off-peak charging would be more noticeable even for wealthy early adopters of EVs.

In addition, state of the art gadgets such as smart phones could play a role for more efficient functioning of DSM measures (i.e. these applications could make it more convenient to use off-peak charging by managing it from home). Therefore, a reduction in demand for home charging as a result of DSM measures is estimated to be between 5 (equal to DSM effectiveness for conventional electricity demand) and 15% in this study. Although some uncertainties are involved in predicting the upper limit of effectiveness of DSM measures, the limit is assumed to be slightly larger than the effectiveness of DSM for conventional electricity demand. This is assumed to be caused by the price incentive (if different meters are in place) and ease of application (if for example accompanied by smart applications). Since the reduction achieved by DSM is due to the individuals' willingness to use either cheaper or cleaner electricity, it is assumed that the reduced demand would be distributed during the off-peak hours when the electricity is both cheaper and cleaner (Figure 9).

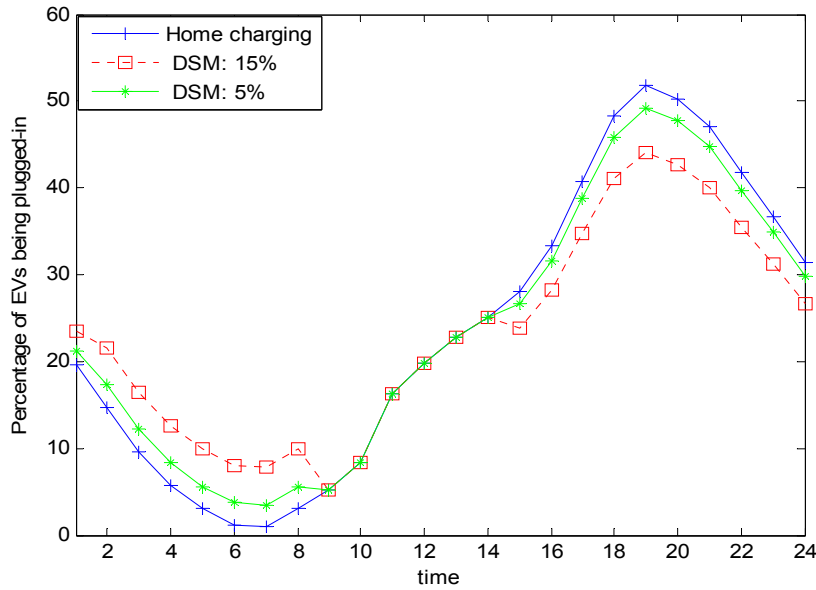


Figure 9: DSM Charging scenario

3. Results: Effects on Electricity Sector and Mitigation

3.1 Effect of EVs on the Electricity Sector

The effects of the charging pattern scenarios (described in Section 2) on EVs' electricity demand are presented here. Subsequently, the importance of load shifting measures when considering the electricity system as a whole (i.e. both EVs' and conventional electricity demand) is discussed.

3.1.1 Hourly Electricity Demand by EVs

Impacts of load shifting measures on the overall electricity demand of EVs are examined in this subsection. The charging patterns described in Section 2, the number of cars (BEVs and PHEVs) predicted in the BAU scenario, and a charging power of 2.2 kW are used to evaluate the impact of load shifting measures on the EVs' hourly electricity demand. A summary of the assumptions for developing this scenario is presented in Table 4.

Table 4: Key assumptions for energy requirements of battery charging

Parameter	Value	Source/Justification
Maximum distance on electricity	100 km	Maximum distance that a BEV/PHEV(60) could go with electricity (BERR and DfT, 2008) (see section 2)
Energy required for full recharging of a depleted battery	20 kWh	This is based on the battery capacity for driving up to 100km on electricity and the energy demand of 0.2 kWh/km.
EV recharge efficiency	90%	Based on an optimistic view of charging efficiency (Valøen and Shoesmith (2007) cited in Element Energy (2009))
Recharger Power	2.2	Calculated based on the energy consumption of EV, recharging efficiency and 10 hours of recharging time.

The hourly additional generation capacity needed to meet the electricity demand by EVs and the effect of load shifting measures (i.e. work charging, fast charging/battery exchange and DSM) on demand in a typical day in 2030 are shown in Figures 10 and 11 (for Min-BAU¹² and Max-BAU¹³ scenarios). For analysing the effects of all demand shifting measures it is considered that the effectiveness of individual policies (i.e. when only a particular policy is in place) is not necessarily equal to that of the selected policy when it is combined with other policies. In other words, the overlaps and/or interactions between these policies are taken into consideration. For example, as discussed in Section 2.4.6 battery exchange and fast charging are considered as inter-independent and when assessing their effects, they could not be considered in separation each other (Set Theory¹⁴). However, the schemes might intensify the effects of each other. On the other hand, among the load shifting measures which were introduced in Section 2, some of them show independent behaviour. For

¹² BAU scenario for car uptake and minimum effectiveness of load shifting measures.

¹³ BAU scenario for car uptake and maximum effectiveness of load shifting measures.

¹⁴ Set theory: Union of the sets A and B ($A \cup B$), is the set of all objects that are a member of set A, or B, or both. In other words, $(A \cup B)$ equals $A+B-(A \cap B)$ where $(A \cap B)$ is the intersection of sets A and B.

example, DSM is expected to be independent even when other load shifting policies are in place. These interactions are taken into consideration when developing Min-BAU and Max-BAU scenarios.

Figure 10 shows the effect of simultaneous implementation of load shifting measures (using the lower limits of effectiveness) would result in a 17% reduction in EVs' peak demand - compared to the home charging scenario.

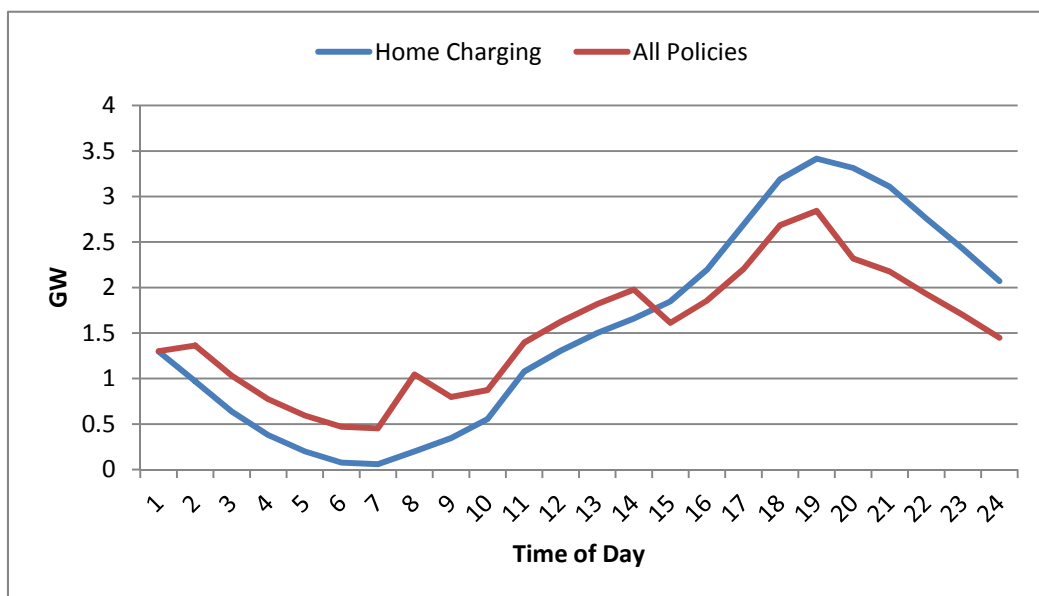


Figure 10: Hourly electricity capacity required to meet the demand from EVs – Min-BAU Scenario

Similarly, Figure 11 shows the effects of simultaneous implementation of load shifting measures considering the upper levels of effectiveness for each measure. As shown in the Figure, if all the measures are effective (upper level of effectiveness), the EVs' electricity demand variability will be minimized within the range of 1 to 2.5 GW during the conventional electricity demand non-peak hours and it will almost reach zero during the time when the conventional electricity demand is the highest (between 7:00 p.m. and 9:00 p.m.).

The results shown in Figure 11 present a situation in which load shifting policies show their maximum effectiveness. In practice, not all the consumers would totally disregard home charging as the most convenient and most reliable way of charging. In other words, although the overall conclusion of effectiveness of load shifting policies are still valid, the findings shown in Figure 11 (near zero electricity demand during peak hours) are depicting a very optimistic scenario which is shown here to outline the extreme of load shifting effectiveness (the least electricity demand which is necessary for providing electricity for EVs at peak hours).

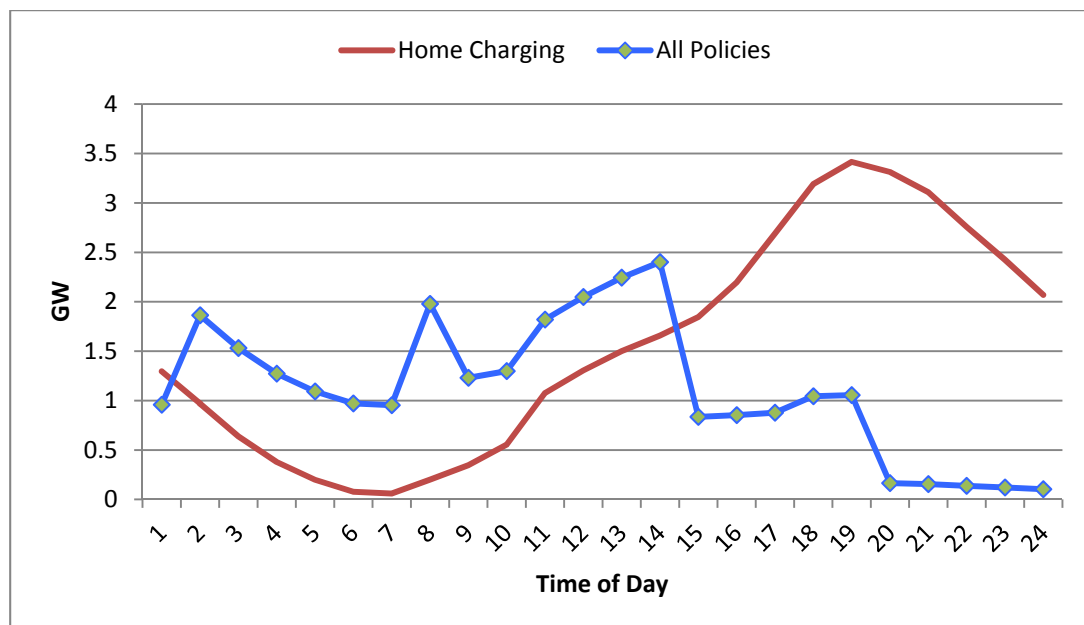


Figure 11: Hourly electricity capacity required to meet the demand from EVs – Max-BAU Scenario

3.1.2 Overall Conventional and EVs' Electricity Demand

This section investigates the impacts of load shifting measures when analysing the whole system (i.e. considering both conventional electricity demand and electricity demand from EVs). The hourly conventional electricity demand in a typical day in

2030 as predicted by the National Grid (NG, 2010a), is shown in Figure 12. The effects of non-managed and managed (upper level of effectiveness of load shifting measures) electricity demand by 3,000,000 EVs (total number of BEVs and PHEVs in 2030 under the BAU scenario) on the overall electricity demand is shown in Figures 13 and 14 respectively.

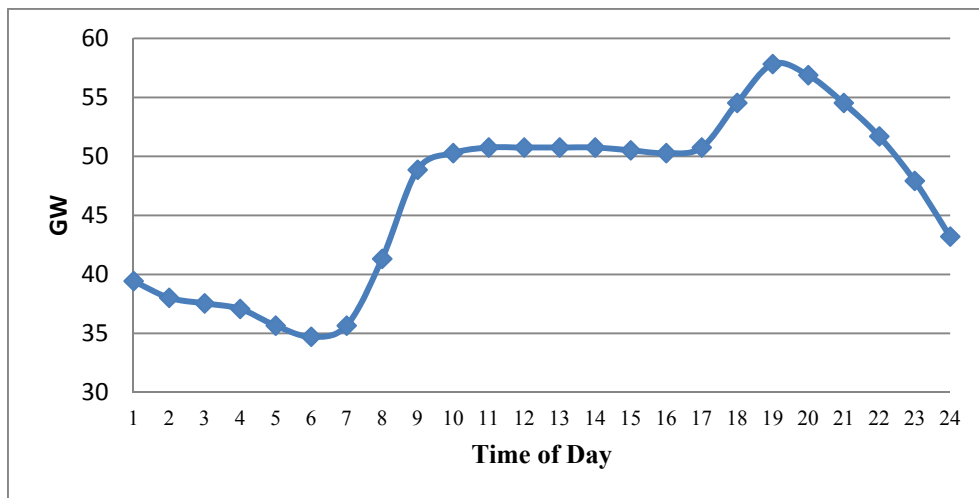


Figure 12: Hourly electricity generation capacity needed to meet the conventional demand in a typical winter day in 2030.

Source: NG (2010a)

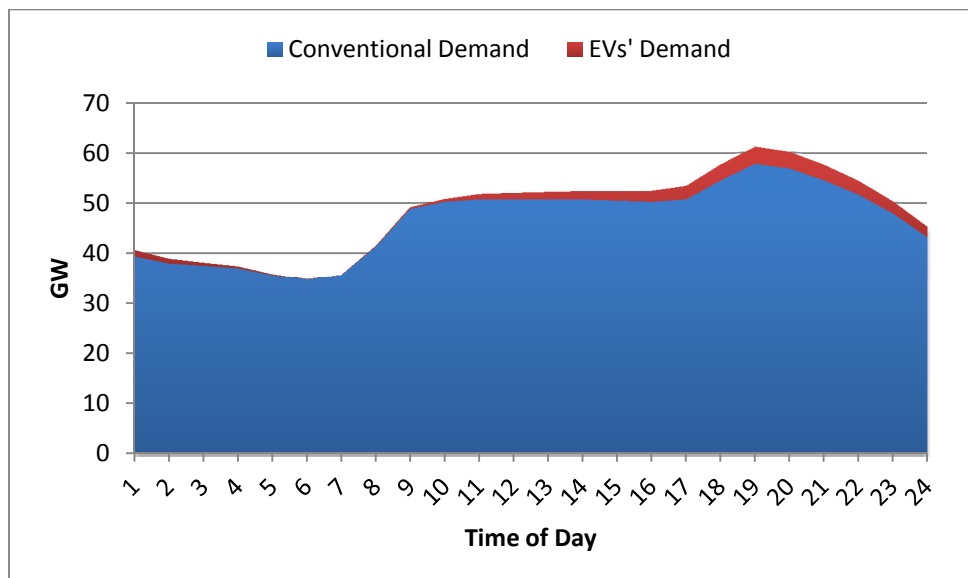


Figure 13: Effects of non-managed electricity demand by EVs on generation capacity required to meet the overall demand - 3,000,000 EV

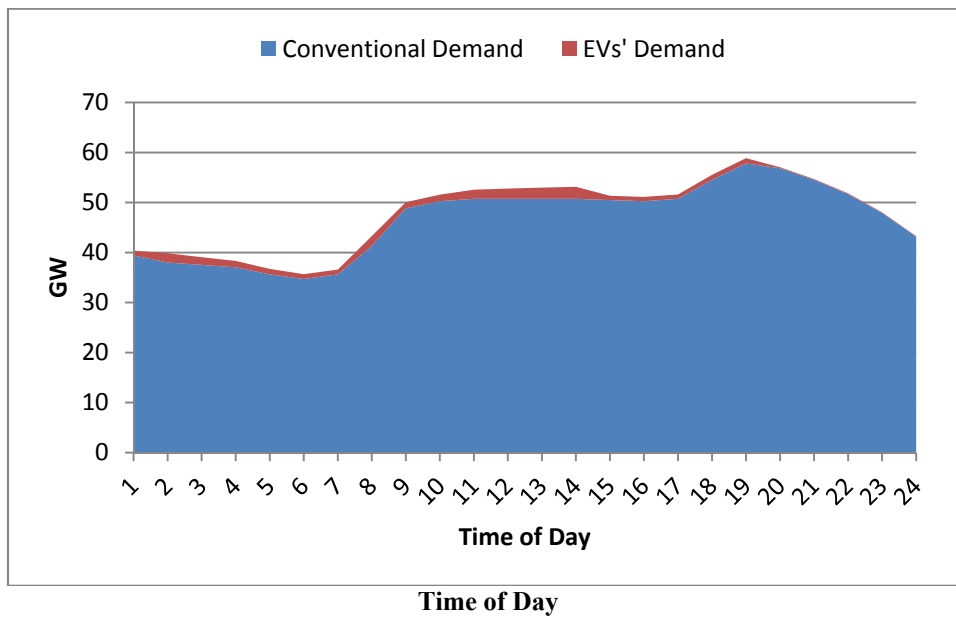


Figure 14: Effects of managed-EVs' electricity demand on the electricity capacity needed to meet the overall demand - 3,000,000 EVs

The effects of the load shifting become more apparent as the number of EVs increases. The impact of non-managed and managed (upper level of effectiveness) electricity demand from EVs considering the High-Range scenario for EV uptake, (11.2 million EVs (BEV and PHEV) in the fleet in 2030) on overall electricity demand are shown in Figures 15 and 16 respectively. Clearly, if electricity demand by EVs is effectively managed, it will not add a substantial load to the conventional electricity demand at the peak hours. More precisely, if electricity demand by EVs is not managed, the required capacity to meet this demand would reach a maximum of 12.7 GW at 7 p.m. Whereas 3.9 GW is the maximum capacity needed to meet this demand when load shifting measures with maximum effectiveness are in place. Therefore a 31% reduction in generation capacity to meet the peak demand for EVs is achievable through effective load shifting measures.

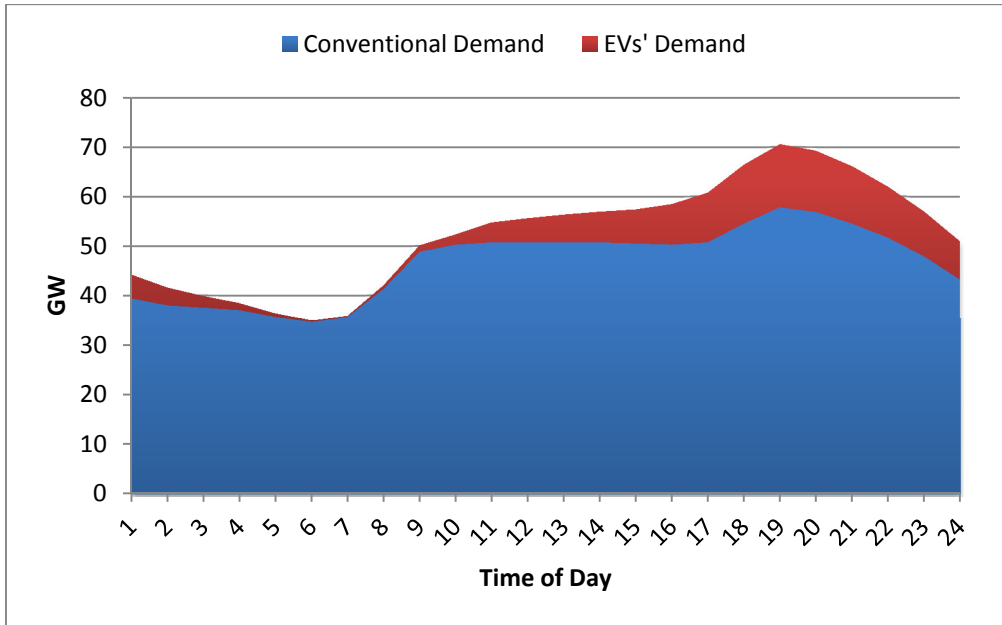


Figure 15: Effects of non-managed electricity demand by EVs on generation capacity required to meet the overall demand - 11,200,000 EVs

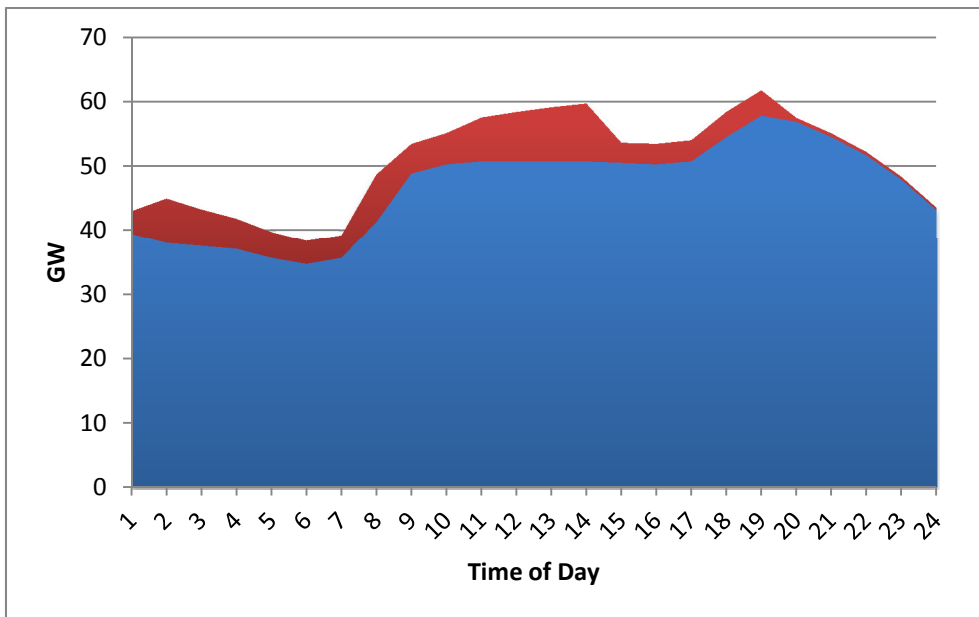


Figure 16: Effects of managed electricity demand by EVs on generation capacity required to meet the overall demand - 11,200,000 EVs

When considering the electricity system as a whole (i.e. both EVs’ and conventional electricity demand), without implementing load shifting measures the overall capacity needed to meet the peak load would be 70.6 GW (18% of which is caused by EVs)

whereas if load shifting measures are implemented effectively, it would decrease to 61.8 GW (6% of the overall demand is from EVs) representing a 12% reduction in peak generation capacity needed to meet the overall demand.

3.2 Emission Scenarios for EVs

The following sections discuss the results of the emission mitigation scenarios. The first scenario constitutes a ‘baseline’ scenario which serves as a reference point or benchmark for comparisons. Since the main purpose of this section is to explore the effects of EVs on CO₂ emissions, by using a conservative approach it is assumed that in the baseline emission scenario, no EVs will enter the fleet during the time period of the study. The second and third scenarios are EVs-BAU and EVs-HR scenarios which are developed based on the BAU and HR EV uptake scenarios respectively. These two scenarios are developed to consider the effects of rate of EV uptake on the overall emissions from the fleet.

3.2.1 Emission Scenario 1: Baseline Emission Scenario

For developing the Baseline Emission Scenario, the effects of two factors are considered to be important: the emission factor of the car (i.e. gCO₂/km) and the total yearly Vehicle Kilometers Travelled (VKT).

Emissions Factor

Although in the baseline scenario, it is considered that zero EVs would enter the fleet, the gradual improvement in conventional car technology is taken into consideration. Average emissions from light duty vehicles is assumed to be 130 and 95 gCO₂/km in

2020 and 2030 respectively which is calculated using the European Car's Standard Regulations (IES, 2010).

As the European standards for new car emissions are set for 2015 and 2020 (130 and 95 gCO₂/km respectively), the assumptions of the current study build in a delay. This delay is considered in this study due to the fact that historically average emissions from the fleet (both new and old vehicles) have been higher than the average emissions of new vehicles. For example, the government estimates that in 2009 average CO₂ emissions from the passenger car fleet was around 180 gCO₂/km, with the new car average emissions for 2006 being 167.7 gCO₂/km (DfT, 2007a). Therefore, given the normal lifetime of vehicles in UK (10 years), the average emissions level from the vehicles is estimated to be 130 and 95 gCO₂/km in 2020 and 2030 respectively.

Vehicle Kilometer Traveled

Based on the UK travel survey in 2009, the yearly average distance that each car travels decreased by 0.85% in the time period between 1995-2012. This is basically because of the increase in the number of the cars per household (DfT, 2012). However, for simplicity, the yearly average distance that each car travels is assumed to remain constant in this study. In other words, if a typical car traveled "X" kilometers in 2010, a typical car in 2030 would also travel "X" kilometers. Therefore, all the increase in demand for travel in the country (from 416 billion kilometers in 2010 to 507 billion kilometers in 2030 (BERR and DfT, 2008) is attributed to the increase in the number of cars on the fleet rather than change in the travel behaviour of individuals.

In summary, the baseline scenario assumes that two factors are changing over time: (1) the total demand for travel is expected to increase (despite the constant VKT of a single car), and (2) average emissions per kilometre are expected to decrease due to technological improvements. Given the above two factors, the projections of CO₂ emissions from conventional passenger cars between 2010 and 2030 are calculated and are shown in Figure 17.

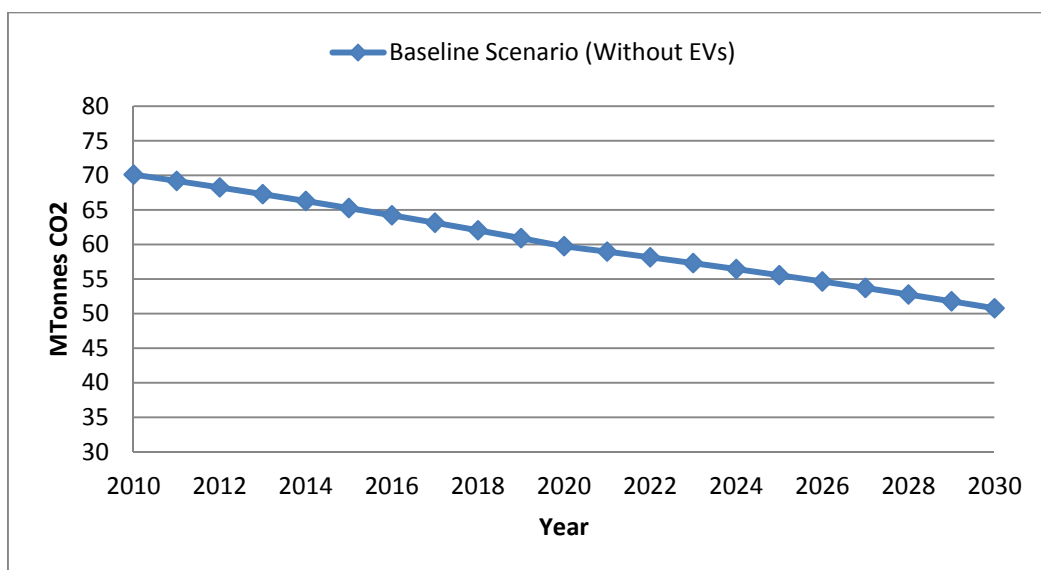


Figure 17: Emissions from passenger cars in the absence of EVs (Mtonnes CO₂)

The results of the Baseline Scenario (Figure 17) show that the overall CO₂ emissions are expected to decrease by 27.6% from 70.1 Mtonnes CO₂ in 2010 to 50.8 Mtonnes CO₂ in 2030. The decreasing trend of the emissions is mainly due to improvement in the vehicles' technology.

More precisely, although the emission factor of a single car would improve by more than 47% (from 180 gCO₂/km in 2010 to 95 gCO₂/km in 2030), the achievable emission reduction potential from the fleet would be limited to 27%. This is mainly

because of the 17% increase in the number of cars on the fleet during the time period of study (from 28.9 million in 2010 to 34.8 million in 2030 (BERR and DfT, 2008)).

3.2.2 Emission Scenario 2: EV-BAU

In the EV-BAU emission scenario we examine the effects of the lower limits of the load shifting scenarios described in Section 2 (see Table 5).

Table 5: Assumptions for Developing EV-BAU Scenario

Effectiveness of load shifting scenarios (Considering home charging as the basis)	
Workplace Charging	10%
Fast Charging/Battery Exchange	15%
DSM	5%
Number of EVs	Following the assumptions in Table 1 for BAU Scenario
Charging Power	2.2 kW
Emission From Marginal Plant	Following the assumptions in Figure 1

Total number of cars (EVs and ICEs) in the fleet is assumed to be comparable in both baseline scenario and the EV-BAU scenario. However, while all of the new cars entering the fleet are assumed to be ICEs in the baseline scenario, in the EV-BAU scenario, a portion of the new cars which enter the fleet are electric vehicles (following the BAU scenario for car uptake as discussed in Subsection 2.2).

Based on the number of cars using electricity at each point of time, the charging power needed to charge each car and the emissions from marginal power plants, we calculate the emissions trajectory from passenger cars in the EV-BAU scenarios as shown in Figures 18.

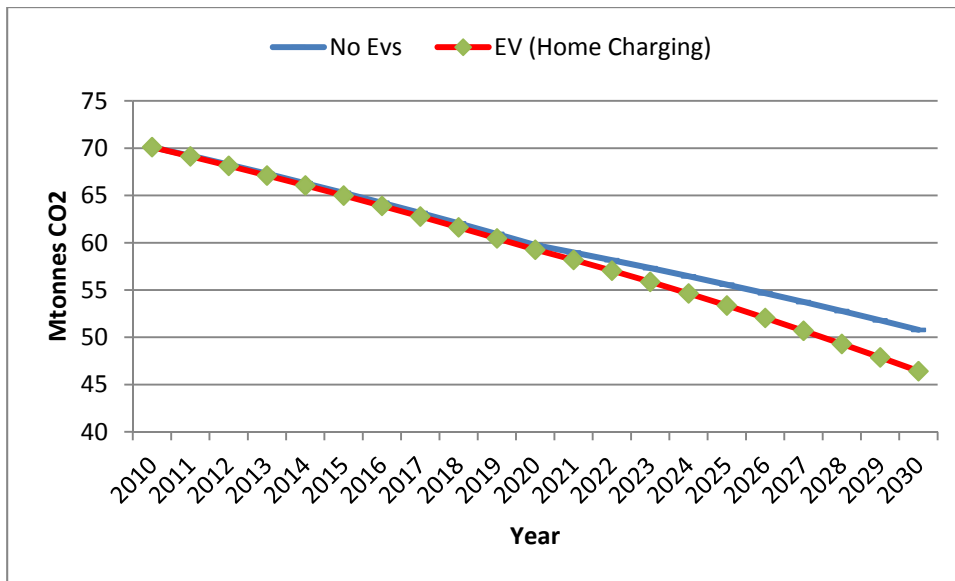


Figure 18: Emissions from EV-BAU Scenario

The results which are shown in Figure 18 indicate that EVs are effective in CO₂ emission reduction even compared to the advanced ICEs. More precisely, while 27% emission reduction from 2010 level is achievable through introduction of advanced ICEs in the fleet in 2030, introduction of EVs (following the BAU car uptake scenario) is found to further improve the mitigation potential from the fleet by another 7%. In other words, simultaneous introduction of EVs and advanced ICEs to the fleet would reduce the CO₂ emission from 70.1 Million tonne in 2010 to 46.4 Million tonne in 2030.

3.2.3 Emission Scenario 3: EV-HR

EV-HR scenario is developed in order to analyse the sensitivity of the results to the number of EVs entering the fleet. All of the assumptions in this scenario are comparable to those considered for developing EV-BAU except that of the number of EVs entering the fleet. In this scenario, we assume that number of EVs would be

similar to those of the HR scenario as discussed in table 1. The results of EV-HR scenario are shown in Figure 19.

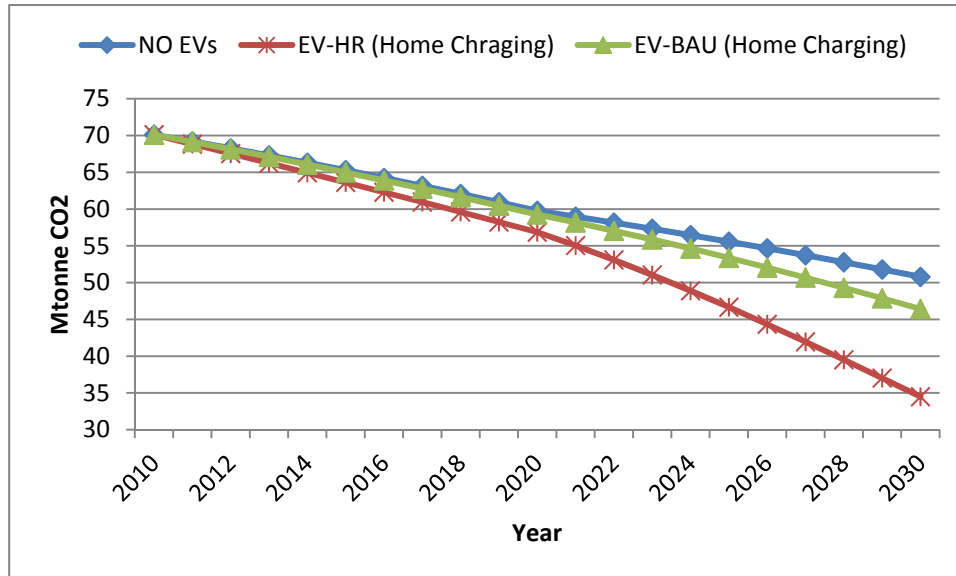


Figure 19: Emissions from EV-HR Scenario

Predictably, the increase in the number of EVs would result in a higher emission mitigation potential from the fleet. Results of Figure 19 show that introduction of EVs to the fleet (following the HR EV uptake scenario) and advance ICEs would lead to about 50% less emission from the fleet in 2030 compared to 2010. The results shown in figure 19 can be used as a good indicator to assess the effects of EVs and ICEs on overall mitigation potential from the fleet. While in 2030, the share of advance ICEs are 68% of the total cars on the fleet, their effectiveness is limited to the 53% of the overall emission reduction. In other words, 47% of the overall emission reduction in 2030 is achieved via introduction of EVs with a share of only 32% of the total existing cars on the fleet.

3.2.4 Effects of Load Shifting Measures on Emissions

We compared different load shifting measures in order to investigate their effects on the overall emissions of EVs (Figure 20). In addition, we investigate a very optimistic situation in which all the load shifting measures are in place and their effects are additional to each other. The results of this analysis are shown in Figure 21.

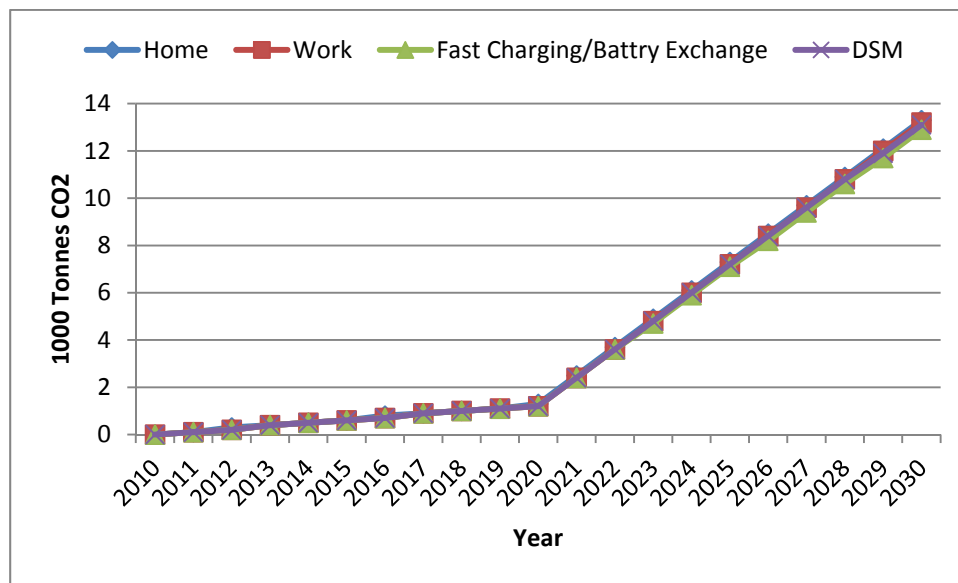


Figure 20: Effects of Load Shifting Measures on Emissions

Figure 20 shows that in 2030 the impacts of load shifting policies are limited to the order of 1,000 tonnes of CO₂ compared to around 24 million tonnes of CO₂ emissions reduction achievable through introduction of EVs under the BAU scenario. The results of load shifting measures on the emissions from EVs (under BAU uptake scenario) are presented in the figure. As shown, the effect of charging pattern on CO₂ emissions is found to be relatively small.

This result relies on the assumption that emissions from the marginal power plants remain almost unchanged during 16 hours of the day (i.e. from 8:00 to 24:00) (Figure

3). Therefore the distribution of vehicles charging at different times during these 16 hours has little effect on the amount of emissions. In other words, since between 00:00 and 8:00 the emission factor of the marginal plant is noticeably less than the rest of the day, the determining factor of the overall emissions from EVs is the number of cars plugged-in during the off-peak period (between 00:00 and 8:00 a.m.) and that does not vary noticeably between different charging scenarios.

However, in a very optimistic situation where all the load shifting measures are in place and their effects on load shifting are additional to each other, implementation of load shifting measures could result in further emission reduction from the fleet (Figure 21).

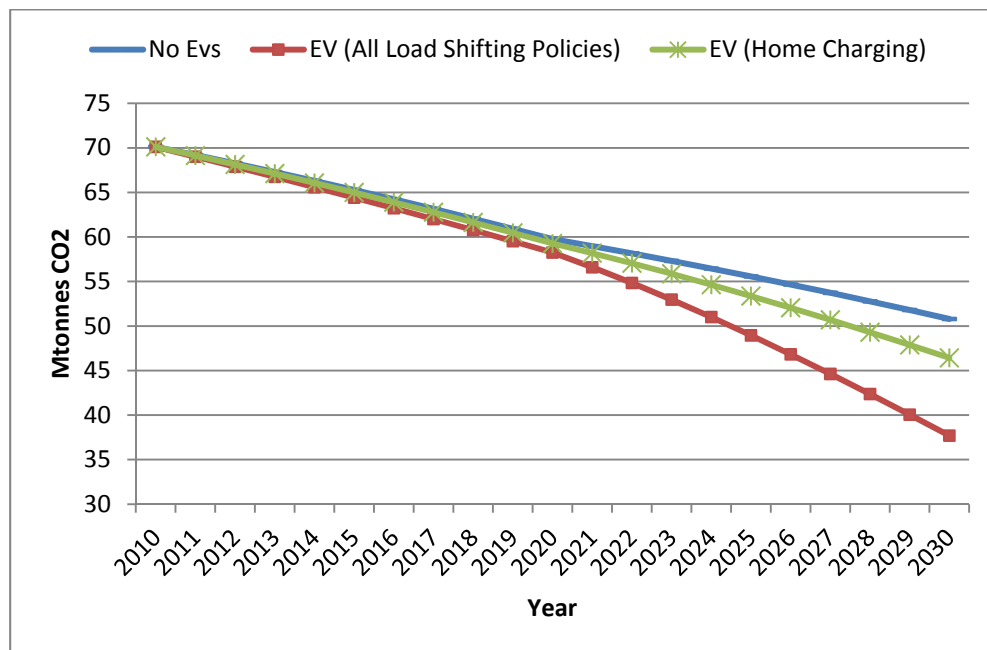


Figure 21: Effects of Load Shifting Measures on Emissions (Optimistic Scenario)

As shown in Figure 21, the effects of implementation of load shifting measures (lower limits of effectiveness) on the overall achievable emission reduction from the fleet under the EV-BAU scenario. The results show that in 2030, emissions from the EV-BAU scenario is 46 million tonnes CO₂ which is 8% lower than the emission from baseline scenario in which no EVs are in the fleet. Comparing this with the very optimistic case in which the effects of all load shifting policies are additional, we can conclude that the effects of load shifting measures is further reduction of the emission to 37.7 million tonnes CO₂ which is 26% lower than baseline. However, it should be highlighted that this case is unlikely to materialize. Because this scenario assumes that all the individuals are willing to use alternative charging rather than home charging. In the real world, not all the individuals will shift from home charging and therefore this scenario illustrates the maximum effectiveness of load shifting measures for emission reduction.

4. Discussions and Sensitivity Analysis

There are several factors which could affect the results of the current analysis chief among them are number of EVs entering the fleet. Charging behaviour of individuals, energy performance and technology improvement of the EVs and the emission factor of the electricity generation system are also important.

4.1. Number of Cars

The effects of number of cars on both the electricity demand from the fleet and the emission reduction potential of EVs have been discussed comprehensively in Subsections 3.1.2 and 3.2.3 respectively.

4.2. Individuals' Behaviour

In order to assess the sensitivity of the results to individuals' behaviour, different ranges were examined for different load shifting policies. These ranges were considered to account for the uncertainties in the assumptions. Several of these assumptions were built upon the results of the survey conducted by Element Energy (2009) among owners of EVs or individuals who were considering buying EVs. Respondents to the survey were among four different groups as shown in Table 6.

Table 6: Survey Sample Size (Element Energy, 2009)

Group	Number of Respondents
Household EV Owners	36
Commercial EV Owners	11
Household Considering Owning an EV	215
Commercial Operators considering Owning 1 or More EVs	16
Total	278

The number of EV owners is very small in the sample and a small difference in response would lead to high percentage changes in the overall results. In order to avoid such a misinterpretation, for developing charging scenarios responses of all of the participants in the survey were taken into consideration. This way, the sample size increased to 278 participants which is large enough to provide statistically significant and meaningful insight into the behaviour of early adopters of EVs (Element Energy, 2009).

4.3. Charging Power

Another area of uncertainty is the electric power used for charging the EVs. As discussed in Section 2.1, a range of 0.2 to 0.26 kWh/km is reported in the literature to represent the vehicle performance of EVs (Stephan and Sullivan, 2008; Element

Energy, 2009). Throughout this study we use 0.2 kWh/km. In addition, to account for the sensitivity of the results to the vehicle performance, vehicle performance of 0.26 kWh/km with a charging power of 2.9 kW is examined in this section and its effects on both electricity demand from EVs and CO₂ emissions from the fleet are presented in Figures 22 and 23 respectively.

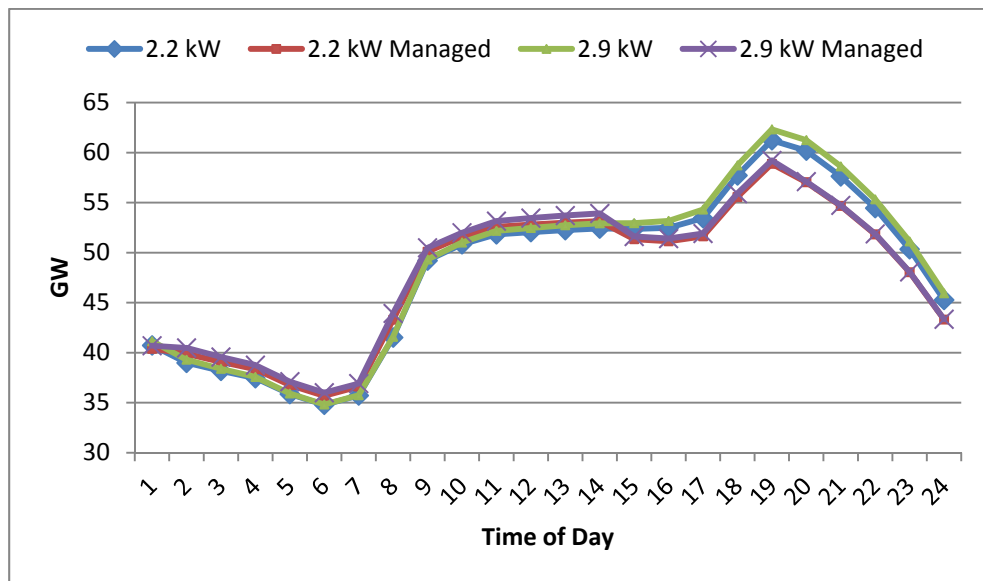


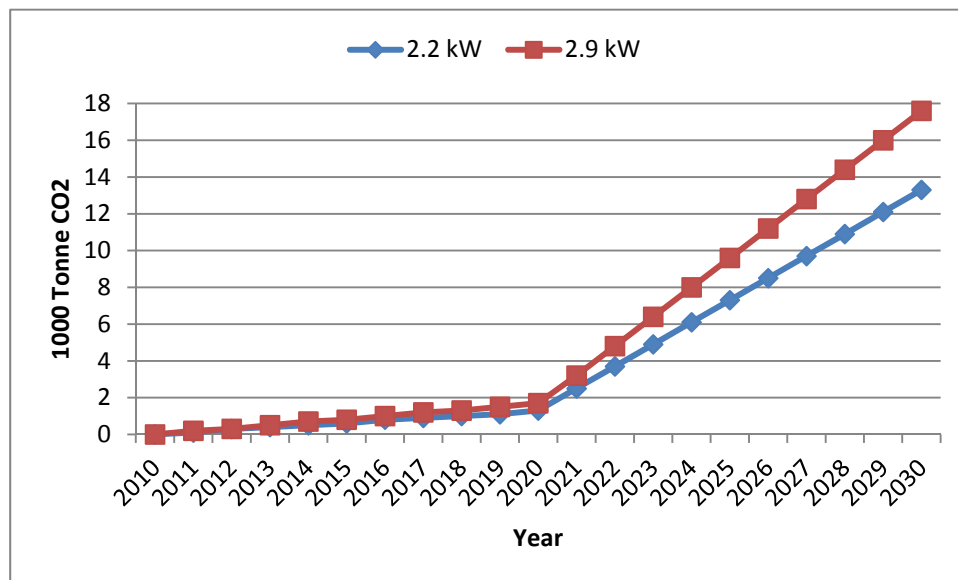
Figure 22: Effects of Charging Power on the Overall Electricity Demand (for BAU Scenario for EV uptake)

It is shown in Figure 22 that if electricity demand of EVs is not managed, increase in the charging power from 2.2 to 2.9 kW would result in 1.8% increase in the overall peak electricity demand. However, if the electricity demand is managed, this increase would be limited to about 0.5% of the overall electricity demand in peak hours.

Therefore, if load shifting measures are in place, because the managed EVs demand is substantially small compared to the overall demand in peak hours, small changes in EVs electricity demand would not make noticeable changes in the overall peak electricity demand.

Effects of Charging Power on Emissions

The results of Figure 23 show that although vehicle performance (kWh/km) and the charging power needed for charging EVs are effective factors while assessing the emission factor of an individual EV, when considering a large number of EVs, the effects of vehicle performance on overall emission from the fleet is limited to orders of 1000 tonnes of CO₂. Whereas the effect of the number of EVs on emissions is found to be more substantial (Section 3.2.3).



**Figure 23: Effects of Charging Power on the Emissions From EVs
(Following the BAU Scenario for EVs uptake)**

4.4. Emission Factors

Although using emissions rates from marginal power plants may be methodologically more realistic for calculating the real emissions from EVs (McCarthy and Yang, 2010), the hourly average emissions from power generation could also be used for calculating the emissions attributed to EVs. This is used to analyse the sensitivity of the results to the emission factors. The average hourly emissions from power plants in

the UK are estimated to be similar to those shown in Figure 24 in a typical day in 2030 (Elementenergy, 2009). The low emissions factor shown in the figure reflects the ambitious targets of the government to increase the share of renewable energy sources.

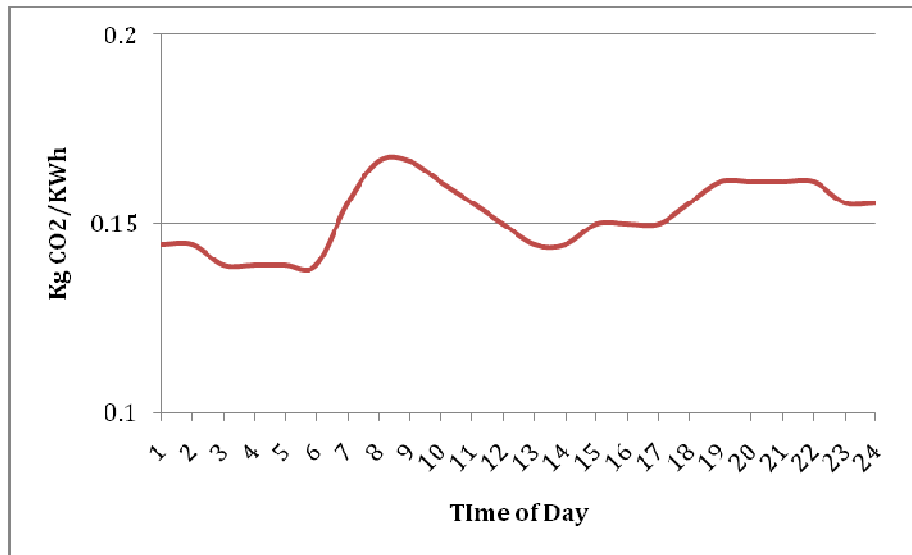


Figure 24: Average hourly emissions per kWh in 2030

Source: Elementenergy (2009)

The predicted emission pattern shown in Figure 24 indicates that the trend in emissions is almost stable at around 0.15 kgCO₂/kWh without major fluctuations during the day. Therefore, it can be concluded that the distribution of vehicles charging at different times (due to implementing different demand shifting measures) would not result in a big differences in the overall CO₂ emissions.

However, if instead of emission factors from marginal plants, average emission factors of grid are used, the emission mitigation potential of EVs will increase. More precisely, in 2030 the average emission factor from electricity production is predicted to be less than ½ of the CO₂ emissions from the marginal power plant (considering

daily average). Therefore, for calculating the mitigation potential of EVs, if instead of using marginal emission, the average emission for the grid is used, the achievable emission reduction potential of EVs would be 240% higher (Figure 25). However, as the emissions from the EVs are 1000 order of magnitude less than the overall emissions from the fleet (i.e. considering both ICEs and EVs) it can be concluded that if instead of marginal emissions, average emissions are used for the calculation, the overall mitigation potential from the fleet would not change substantially.

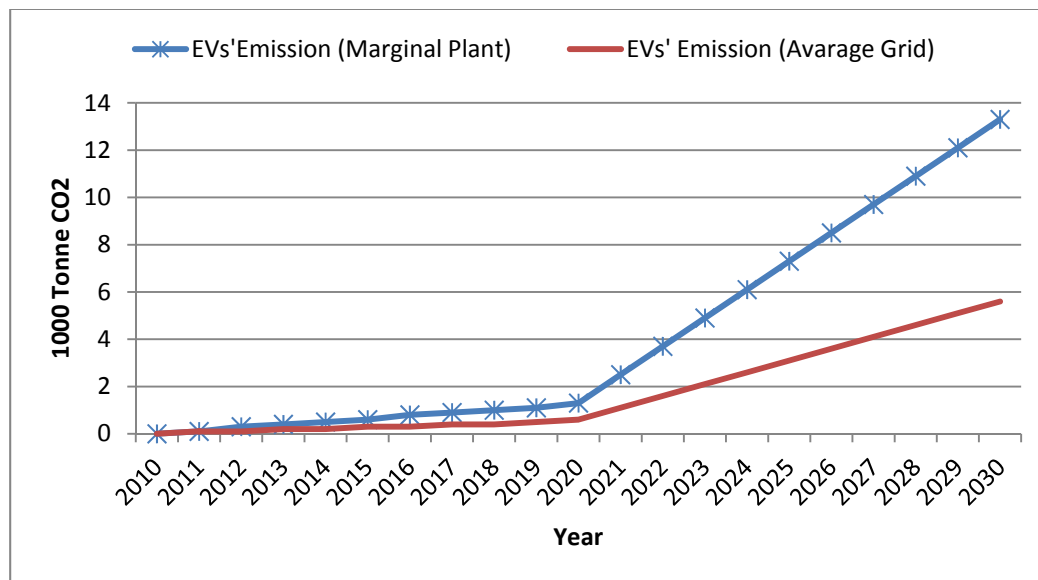


Figure 25: Effects of Emission Factors on the Overall Emissions from the EV Fleet (Following the BAU Scenario for EVs uptake)

5. Conclusions

The analysis in the paper is a theoretical exercise (rather than forecasting any future scenarios) designed to give insights into the mitigation potential of EVs and their effects on the electricity sector. Therefore, the need for translating the findings in this paper into the policies which could be implemented in real world is a necessity which should be addressed in future works.

We show that effective implementation of EVs load shifting policies would not only reduce the EVs' electricity demand by up to 33% at peak times, it would also help leveling the electricity demand curve and therefore improve the overall efficiency of the system. This would lead to more effective use of the existing capacity and would reduce the overall cost of electricity for all consumers including both EV and non-EV users. More precisely, effective implementation of load shifting measures would lead to a higher load factor of the existing power plants which itself helps reducing the need for new generation capacity. The avoided cost for constructing new electricity generation and distribution infrastructures would result in cheaper price of electricity per kWh for the consumers.

Since emission factors for the electricity grid vary with time, it was expected that time of charging would affect the emission performance of EVs. However, evaluation of this hypothesis in the UK context indicates that time of charging would not have significant effects on the mitigation potential of EVs mainly because emissions from the marginal power plants remain almost unchanged during 16 hours of the day (i.e. from 8:00 to 24:00) and distribution of vehicles charging at different times during these 16 hours has little effect on the amount of emissions.

The analysis shows that the effects of load shifting measures on the overall emissions from the fleet would be limited to several kilo tonnes of CO₂ which is negligible when compared to several million tonnes CO₂ emission reduction achievable through introduction of EVs to the fleet.

Overall, the results indicate that overall mitigation potential of EVs is a direct function of the numbers of EVs as would be expected and different charging patterns have minimal impacts on the achievable emission reduction potential of EVs.

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