Estimating the grid payments necessary to compensate additional costs to prospective electric vehicle owners who provide vehicle-to-grid ancillary services

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Abstract

The provision of ancillary services in the smart grid by electric vehicles is attractive to grid operators. Vehicles must be aggregated to meet the minimum power requirements of providing ancillary services to the grid. Likely aggregator revenues are insufficient to cover the additional battery degradation costs which would be borne by an existing electric vehicle owner. Moreover, aggregator revenues are insufficient to make electric vehicles competitive with conventional vehicles and encourage uptake by prospective consumers. Net annual costs and hourly compensation payments to electric vehicle owners were most sensitive to battery cost. The fleet provided firm fast reserve from 1900h for 0.42 hours, up to 2.7 hours in the best cases. At best, likely aggregator revenue was 20 times less than the compensation required, up to 27,500 times at worst. The electric vehicle fleet may not be large enough to meet the firm fast reserve power and duration requirements until 2020. However, it may not be until 2030 that enough vehicles have been sold to provide this service cost-effectively. Even then, many more electric vehicles will be needed to meet the power level and duration requirements, both more often and for longer to enable participation in an all-day, everyday ancillary services market.

Keywords: Electric vehicles, Lithium batteries, Vehicle-to-grid, Ancillary services, Battery degradation

1. Introduction

The two aims of this paper are to quantify: first, the battery degradation costs when electric vehicles (EV) are used both to satisfy travel demand and to provide V2G ancillary services; and second, the payments

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necessary from a power aggregator to compensate two group of consumers. The first group comprises existing EV owners who, by the end of the vehicle service life, will want to be left no worse off than if they had not participated in V2G. The second group represents prospective buyers who will compare the costs of EV ownership to that of a conventional vehicle. The motivation for including this second consumer group is that V2G is justified often on the basis that vehicles spend about 95% of their lifetimes stationary [1] and that the revenues from such participation can reduce the costs of ownership [2].

V2G may be used to store electricity generated off-peak which is returned to the grid during peak hours. Net social welfare benefits arise due to avoided construction of peaking generating plant [3]. A recent analysis of the V2G power capacity of a car park showed that 'peak-shaving' and regulation services returned the largest economic value, while spinning reserve could not be delivered profitably [4]. V2G can smooth the variations in output from generating plant using renewable energy sources. For example, EV providing V2G through high power connections reduced excess generation (and associated carbon dioxide emissions) from non-wind facilities and increased the efficiency of the power system [5]. Vehicle-to-building (V2B) is a local variation of V2G which exploits the relationship between commuter and employer. Here, vehicles discharge to the building directly to shave the short peaks in demand which reduces costs to the facility [6]. V2B has a role in the residential context where it can reduce energy costs to the home, provide back-up power and maintain power quality [7].

V2G may be most cost-effective for owners of plug-in vehicles which participate in the short-duration, high-value power market of ancillary services. Specifically, vehicle owners receive two payments: one for the contracted capacity; and the other for the energy delivered. These capacity payments are the basis for V2G competitiveness because they augment the relatively low energy payments, which alone would render V2G unprofitable. The attractiveness of this scheme is dependent on the power level of the connections, vehicle battery capacity and the value of ancillary services [8]. The vehicle owner can benefit from a greater return when both ancillary services and peak power demands are met with V2G, than when each service is provided individually [9].

The UK National Grid uses ancillary – reserve services and frequency response measures – services to balance demand with supply and to maintain the quality of electricity service, respectively. Examples of reserve services include fast reserve and short term operating reserve (STOR). STOR is the extra power necessary, either when actual demand exceeds that forecast, or to account for unavailability of generating plant. Frequency response mechanisms, such as firm frequency response and frequency control by demand management, are used to counter the real-time changes in system frequency when demand and supply are not matched. Frequency falls when demand exceeds supply and can be remedied by either increasing supply or reducing demand. Firm frequency response is a supply-side measure where a minimum 10 MW is injected to the system to counter a fall in frequency. Frequency control by demand management involves interrupting services to customers for no more than 30 minutes[1].

Of the ancillary services, firm fast reserve and firm frequency response may be met best by V2G. The 'firm' relates to the contract which providers enter into with National Grid to provide services on a consistent basis. Both services are attractive to V2G participants because of the two – energy and capacity – payments. Moreover, the time between a dispatch instruction and the duration that power must be fed into the system are short: specifically, firm fast reserve must be provided for a minimum of 15 minutes and start within two minutes of receiving a dispatch instruction [10]; and secondary frequency response must be provided within 30 seconds of an event and sustained for 30 minutes [11].

Overwhelmingly, contributions to the V2G discussion quantify the benefits of such services to the power grid or system operator. The premise of current V2G models is that a vehicle, or group of vehicles, competes in a market to provide ancillary services. Common assumptions of these models include that vehicle batteries are charged fully both at the start of the day and at the time of grid disconnection [12] and charged and discharged at fixed rates [13]. Additional assumptions are that vehicles connect: opportunistically [14], based on widespread charging infrastructure; during the day-time only, such as in the V2B scenario [6]; or during the night-time only [12], such as in the 'valley-filling' approach.

Providing V2G services may accelerate the degradation of EV batteries leading to the need for more frequent replacement [15], with associated costs borne by vehicle owners. Consequently, this work adopts their perspective and considers firm fast reserve (non-balancing mechanism) only as it can provide also some short term frequency control. The work in this paper is set in the UK context where the minimum requirements to provide firm fast reserve ancillary services to the National Grid are a: ramp rate of 25 MW min^{-1}; a total power of 50 MW; a duration of service of 15 minutes; and the service must be in place within two minutes of receiving a request from National Grid [10]. Satisfying these power and energy criteria requires the participation of multiple EV through a power aggregator. Appropriate charging infrastructure, metering, and communications system must exist to support the V2G interaction, the costs of which may not be borne by the vehicle owner alone.

In general, the existing V2G research makes assumptions on one or more of vehicle efficiency, consumer behaviour and battery degradation. Where powertrain modelling is not present, studies are based on either a constant vehicle energy use per distance travelled [16] or battery state of charge dropping linearly with distance travelled [13]. Driver behaviour influences the probability of vehicles being connected to the grid. However, works which do not incorporate real-world travel data make assumptions on at what time and for how long vehicles may be connected. For example, [13] assumed normal distributions for vehicle arrival and departure centred around peak driving hours of 0800h and 1800h. In contrast, this work uses models

[1] The range of reserve services are described online at `http://www2.nationalgrid.com/uk/services/balancing-services/reserve-services/`

of both EV powertrains and battery degradation, paired with national travel survey data to determine the costs to the vehicle owner which need to be compensated by V2G ancillary service provision.

The method presented is flexible and applicable in different national circumstances. There are three bases which support this statement. First, the vehicle market is global. For example, the Nissan Motor Company reported the Nissan LEAF as the best-selling EV, accounting for 45% of the market, having sold 110,000 units globally between December 2010 and June 2014 [17]. Second, similar driving behaviour has been observed in different national travel surveys. In the US, the peaks in trip start times occurred at 0700h and 1700h [18]. Third, ancillary services are a power system requirement which is independent of whether the system operates through markets or remains part a vertically-integrated structure. Indeed, the number of studies investigating V2G ancillary services illustrates a demand for such services across regions and countries.

2. Method

The cost calculation method has three principal elements which addresses assumptions in others' models of energy demand by EV on the grid. The first is an empirically-derived battery degradation model. The second is a validated powertrain model simulated over the New European Driving Cycle (NEDC) to give per second current flows through battery pack while driving. The third is a comparison with the costs associated with the equivalent conventional vehicle to reflect the choices faced by prospective EV owners. Together these form a system which both quantifies and internalises the cost burden on the vehicle (and battery) owner when providing V2G services.

The UK National Travel Survey (UKNTS) [19] provided realistic patterns of vehicle availability for the grid. The UKNTS consists of 1.1 million trips (years 2008-2013). The median velocity, distance travelled and duration are 29 km h^{-1}, 11 km and 0.38 h, respectively. The highest frequency of trip start times in the morning and afternoon occurred at 08:00 h and 15:00 h, respectively; the mean trip interval was seven hours. The probability distribution for vehicle activity in any hour of the day is given in [15].

The UKNTS trip distribution, coupled to opportunistic charging, represents the best case for vehicles to participate in V2G services for two main reasons. The first is that if a vehicle is connected to the grid whenever it is stationary, the battery pack is only depleted by the energy used to deliver the immediate preceding journey. Therefore, the pack will have a high state of charge for meeting grid demands when connected. The second reason is that a vehicle that is always connected when stationary maximises its availability to the grid. Opportunistic charging removes the need to assume specific driver behaviour. However, the driver may choose to charge when it is most disadvantageous to the grid which could have negative impacts at large scale EV deployment.

The Nissan LEAF[2] is the best-selling EV in the UK, with 1,774 registered for the first time in 2013. It was modelled in ADVISOR version 2003-00-r0116 [20] on Matlab R2015a and the costs of ownership compared to the published figures of the Nissan Pulsar as the closest equivalent conventional vehicle from the same manufacturer. The base Pulsar was used with a retail price of £15,995 and fuel economy of 56.5 mpg[3]. Technical specifications for the Nissan LEAF is given in Table **??**.

The Nissan LEAF battery was modelled using a 18650-style Li-ion and designed to deliver 440 W kg^{-1}, 180 Wh kg^{-1} and a maximum 3,000 cycles at 75% depth of discharge (DOD). The degradation model is presented in [21] and validated across a range of C-rates[4] and temperatures. The batteries used in this work may not be the exact type used in the LEAF. However, the battery degradation model used is valid for Li-ion battery chemistries with similar ageing mechanisms to the 18650-style cell. Therefore, the model used is appropriate for the batteries chosen in this paper and is expected to be applicable to real-world EV batteries. The C-rate was fixed at each time step (of five minutes) of both the vehicle driving cycle and V2G participation, but could be different between time steps (quasi-static). Constant current charging and a constant temperature of 298 K were assumed. The end of the battery life was marked by a 20% capacity fade.

2.1. Electricity grid requirements

Firm fast reserve services require an analysis of the availability of power and energy from the vehicles at the fleet level. The distribution of trip start and end times reduced the number of hours which the fleet was available to provide the power level of 50 MW for the 15-minute duration (three 5-minute time steps). The minimum number of vehicles required to meet the power level was:

$$FleetP = P_{dischargeI} \cdot V_{grid} \cdot n; \tag{1}$$

where: $FleetP$ is the fleet discharge power (MW) to the grid; $P_{dischargeI}$ is the probability distribution of discharge current for each time step of the day based on vehicle trip behaviour and charging regime; $n =$ the first assumption of vehicle number at 16,026 which is the quotient of the 50 MW power level target and the 3.1 kW maximum power that the EV can provide on a 13 A, 240 V circuit; $V_{grid} =$ grid voltage of 240 V.

$$n_{level} = \frac{(50 - max(FleetP))}{P_{dischargeI} \cdot V_{grid} + 1}; \tag{2}$$

where: $n_{level} =$ the number of vehicles required to ensure a 50 MW discharge power is achieved;

[2] Nissan LEAF specification: `www.nissan.co.uk` and `www.carfolio.com/specifications/models/car/?car=220715`

[3] See `http://www.nissan.co.uk/GB/en/vehicle/city-cars/pulsar/prices-and-equipment/prices-and-specifications/model-details.107420_105374_105902.html` for Nissan Pulsar technical specifications.

[4] The current necessary to discharge the battery completely in one hour.

For each time step that the power was greater than 50 MW, the preceding (C^-) and following (C^+) time steps were checked to verify a fleet power greater than 50 MW had been achieved to meet the requirement of three consecutive time steps. If this condition was not satisfied, the fleet was increased by enough to close the larger of the two gaps: 50 MW and the fleet power in C^+; and 50 MW and the fleet power in C^-.

Currently, companies tender to provide fast reserve and include the compensation which they are willing to accept for the service. In 2013, median compensation for energy delivered was £145 MWh^{-1} and £805 h^{-1} for committing the plant to be available[5]. The fleet aggregator is expected to receive the revenues of providing ancillary services and distribute the proceeds to the vehicle owners, after covering its costs. The aggregator may employ two strategies to encourage EV owners to participate in providing V2G services. First, EV owners may be allowed to participate on a pay-as-you-go basis, rather than being required to sign a contract. Second, the aggregator may remit an upfront cash payment to the EV owner in exchange for signing a contract [2].

2.2. Costs of ownership and operation

The costs of owning and operating (excluding maintenance) an EV were assessed with and without participation in V2G services. The retail prices for petrol and diesel in 2013 were £1.37 l^{-1} and £1.41 l^{-1} [**?**], respectively. The attractiveness of owning an EV was represented by amortised annual payments which converted the purchase price and ongoing operating costs to a net present value. The interest rate was 1.79%, representing the increase in UK gross domestic product over 2012-13[6].

The compensation to each EV in the aggregator fleet were based on the two consumer types described earlier. Recall the first consumer type is the existing EV owner who wishes to recover any additional costs associated with providing V2G services over the vehicle lifetime. The second consumer type is the prospective EV owner who wishes the V2G compensation payments to cover any costs, beyond those of owning a conventional vehicle, across two time horizons: the first was no financial penalty over the asset lifetime of 7.7 years[7]; and the second was no financial penalty after year two, reflecting the desire of consumers to realise a payback on fuel efficiency expenditures within 18 months [**?**] (Figure 1).

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[5]Plant availability compensation comprised £0 $window^{-1}$ for window initiation, £450 h^{-1} for positioning plant and £355 h^{-1} for committing plant availability. Prices are the median of accepted bids FFES1,2,3 and CRUA-1,4 for 2013. Monthly fast reserve market reports are available at `http://www2.nationalgrid.com/UK/Industry-information/Electricity-transmission-operational-data/Report-explorer/Services-Reports/`

[6]Latest UK GDP deflator figures are available from HM Treasury at `https://www.gov.uk/government/statistics/gdp-deflators-at-market-prices-and-money-gdp-december-2014-autumn-statement`

[7]See UK Department for Transport Table VEH0211, available online at `https://www.gov.uk/government/statistical-data-sets/veh02-licensed-cars`.

3. Results and discussion

The ADVISOR model of the Nissan LEAF over the NEDC produced an energy use of 161 Wh km^{-1} which is 7.3% higher than the published figures of 150 Wh km^{-1}[8]. Daily battery degradation was 0.005% for the EV over two runs of the NEDC, representing the morning and evening trips, and corresponds to a battery lifetime of 12 years with no V2G.

The base case Nissan LEAF provided firm fast reserve by discharging its battery by up to 30% through an aggregator with the results presented in Table **??**. Here, each vehicle: had an all-electric range (AER) of 199 km; used a 24 kWh battery costing £400 kWh^{-1} [**?**]; connected opportunistically to the grid using a 13 A, Level 1 (L1) charger; and replaced the battery when a 20% capacity fade was reached. The battery wear associated with providing firm fast reserve led to degradation costs of £0.17 km^{-1} and a net annual cost of £10,900 per vehicle[9]. The daily battery degradation rate required replacement of the pack every 1.7 years.

Under opportunistic charging, the firm fast reserve requirements were met using 44,300 EV connected for 0.42 h beginning at 1900h. Therefore, the aggregator was likely to receive only £335 (from £805 h^{-1}) for positioning the fleet and making it available. However, the existing EV owner required hourly payments of £37 to leave each owner no worse off over the vehicle lifetime. This compensation was equivalent to £1.6 million for the 44,300 EV fleet. Likewise, a prospective EV owner would need hourly payments of £52 (£2.3 million to the fleet) to be no worse off economically than owning and operating a conventional vehicle over its lifetime. Hourly capacity payments of £64 per vehicle (£2.8 million for the fleet) were needed to reduce the net annual costs to that of a conventional vehicle by the end of the second year. Therefore, the likely aggregator revenues were 4,900-8,400 times lower than what was necessary for all the costs of EV providing firm fast reserve to be recovered.

Sensitivity analyses were performed on the factors affecting EV ownership and operating costs, namely: battery capacity and AER; charging regime; DOD for firm fast reserve; battery cost; charging level; and end-of-life criterion for the battery. The AER desired by the vehicle owner determined the battery capacity for a particular vehicle size and its capital cost. The trip purpose and the availability of recharging infrastructure formed behavioural and technical limits, respectively, to the amount of time and energy that the fleet could provide a V2G service. The DOD of each vehicle battery influenced both its degradation costs and the number of vehicles needed to meet the power level and duration requirements of firm fast reserve. The battery cost was a factor in the vehicle purchase price and ongoing costs associated with battery replacement.

[8]See `http://www.nissan.co.uk/dam/services/gb/brochure/Nissan_Leaf_technical_specs.pdf` for performance and pricing.

[9]Data in the results discussion is rounded to assist in reading and understanding the main arguments. Data to full accuracy is available in the tables.

Finally, the criteria to determine battery end of life impacted the frequency of battery replacement and associated annual costs.

3.1. Battery capacity for AER

The battery capacity varied from 50% to 150% of the base case, corresponding to an AER range of 89-238 km. Battery degradation increased as a quadratic with battery capacity ($R^2 > 0.99$) and net annual costs rose 2.8 times over that range, from £5,000 to £14,000 as illustrated in Figure 2a and 2b, respectively.

Battery capacities of 12 kWh and 16 kWh, corresponding to AER of 89 km and 103 km, respectively, would need to be replaced every 2-2.3 years. Larger capacity battery packs would need to be replaced more often at every 1.4-1.9 years. There were three vehicle fleet sizes to meet the firm fast reserve level of 15 MW: 54,300 vehicles for battery capacities of 12 kWh, 16 kWh and 18 kWh; 44,300 vehicles for battery capacities of 21 kWh, 24 kWh and 26 kWh; and 31,800 vehicles for higher battery capacities. Therefore, the vehicle fleet for achieving the 50 MW level decreased as a quadratic with increasing battery capacity ($R^2 > 0.90$).

In half the cases (battery capacities of 16 kWh, 18 kWh, 24 kWh and 26 kWh), no additional vehicles were required to provide meet the 15-minute duration requirement. In the other cases: 63,700 EV were required for battery capacities of 12 kWh; 18,700 EV for battery capacity of 21 kWh; and 16,900 kWh for capacities of 30 kWh and 32 kWh. These larger fleets were generally connected for longer, ranging from 1.6 h for fleets with 30 kWh battery pack capacity up to 2.7 hours for fleets with 12 kWh battery packs. All start times were 1900h because vehicles charged opportunistically. Total fleet sizes for each AER are shown in Figure 2c.

Across all battery capacities, the smallest hourly payments were observed for the smallest battery capacity of 12 kWh, shown in Figure 2d. Here, the EV owner required £1 h^{-1}, equivalent to £145,000 to the whole fleet, to recover battery degradation costs associated with providing firm fast reserve. The aggregator might expect to receive £2,100 from the grid for making the fleet available for 2.7 hours. Therefore, the likely revenues to the aggregator was 65 times lower than the minimum payments to the EV owners. Prospective EV owners required hourly payments per vehicle of £2 and £5 if they were to be no worse off than owning a conventional vehicle over its lifetime or after two years, respectively. These hourly payments were equivalent to £243,000 and £584,000, respectively and were 110 times and 270 times lower than what the aggregator might receive, respectively. Full results are given in Table **??**.

3.2. Charging regime

Sensitivity to V2G services was evaluated based on charging behaviour – opportunistic, at home only or at work only (Figure 3) – and the amount of energy the battery was permitted to discharge.

Opportunistic and home only charging required 44,300 EV each to meet the 50 MW power level and the 15-minute duration requirements of firm fast reserve. In both cases, fleets connected at 1900h for 0.42 h.

However, charging at work only needed 54,300 EV to provide 50 MW for 15 minutes which occurred at 0930h for 0.25 h. Battery degradation costs per km fell from £0.17 for opportunistic charging to £0.13 when charging at work only and £0.12 at home only. Similarly, annual costs fell from £10,900 for opportunistic charging to £7,500 when charging both at home only and at work only. Restricting charging to one of these two locations led to battery lifetimes of 2.3-2.4 years).

For home only charging, the aggregator would be required to make hourly per vehicle payments to the EV owner of £20 to cover the additional battery degradation costs associated with providing firm fast reserve. A prospective EV owner would need to receive £30 and £61 to make the EV no more expensive to own and operate compared to a conventional vehicle with eight years and two years, respectively. Opportunistic charging led to battery lifetimes of 1.7 years and required payments from the aggregator of £37 to the existing EV owner and £52 and £64 to the prospective EV owner for payback within two years and over the vehicle lifetime (4,900-8,400 times what might be received), respectively. Hourly payments for work only charging to existing EV owners would need to be £33 and to prospective EV owners of £50 and £100. These payments to the fleet exceeded the £805 per hour which the aggregator was likely to receive by 2,700-27,500 times across the three charging regimes. Full results are given in Table **??**.

3.3. Individual vehicle battery DOD for firm fast reserve

As battery DOD increased for the EV, battery degradation costs increased linearly as shown in Figure 4a. However, battery replacement was annual across the DOD range. Therefore, net annual costs were fixed at £10,900 and illustrated in Figure 4b. Total vehicle fleet size increased linearly with increasing battery DOD ($R^2 > 0.96$). In every case, save DOD = 40%, no additional vehicles were required to meet the 15-minute duration requirement, as shown in Figure 4c. Here, blue and yellow bars represent the number of vehicles required to the meet the power level and duration, respectively. The median connection time across the DOD range was 0.42 h (0.33-0.50 h) beginning at 1900h. Hourly payments decreased as a quadratic with increasing DOD range ($R^2 > 0.99$) across the two consumer groups. Existing EV owners required a median hourly payment of £37 (£31-46). Prospective EV owners required median hourly payments £52 (£43-65) per vehicle (£1.2-3.5 million for the fleet) and £64 (£53-80) per vehicle (£1.5-4.3 million for the fleet) to be no worse off than owning a conventional vehicle over its lifetime or after the second year, respectively.

For 40% DOD, the firm fast reserve requirement of 50 MW was met by 31,800 vehicles and 16,900 vehicles additional vehicles were required to satisfy the 15-minutes duration. This larger fleet was connected for 1.7 hours beginning at 1900h. Consequently, hourly capacity payments to the aggregator were the largest. The longest connection time coincided with the largest fleet and led to minimum hourly payments of £9 (£452,000 for the fleet) to existing EV owners. This is shown as the smallest stacked bar in Figure 4d. Prospective EV owners required £13 per vehicle (£633,000 for the fleet) to recover costs over the vehicle lifetime and £16 per vehicle (£775,000 for the fleet) within two years, relative to owning a conventional vehicle.

Across the DOD range, the aggregator could expect to receive £270-1,300 from the grid to compensate for being connected for 0.33-1.7 hours. Therefore, the gap between likely aggregator receipts and what would be required by the fleet was 340-16,000 times. Full results are given in Table **??**.

3.4. Battery costs

The sensitivity of net annual costs and capacity payments to battery cost was considered for the range of £200 kWh^{-1} [**?**], as the lower bound expected of future Li-ion battery prices to £800 kWh^{-1} [**?**]. Recent analysis [**?**] suggests current median battery prices are £273 kWh^{-1} (£167-447 kWh^{-1}) using an exchange rate of GBP1 = USD1.5.

The net annual costs of the EV with minimum battery pack cost providing ancillary services was 22% lower than the base case. Fleet size, connection start time and duration were unchanged from the base case. The hourly capacity payments over both horizons increased linearly with battery cost ($R^2 = 1$). The EV fleet with a £200 kWh^{-1} battery pack required an hourly capacity payment of £24 to the existing EV owner to recover additional battery degradation costs. The prospective EV owner required hourly payments of £35 and £44 to be no worse off than owning a conventional vehicle by the end its lifetime and by the second year, respectively. These payments were 3,100 times and 5,900 times, respectively, higher than what the aggregator might receive. Full results are given in Table **??**.

3.5. Charging level

Sensitivity to V2G services was evaluated based on the three charging levels available in the UK: level L1, single phase 12.5 A at 240 VAC; level L2, single phase 21 A at 240 VAC; and level L3, three phase 63 A per phase at 240 VAC[10]. These charging levels were assessed under five charge/discharge combinations: both charge and discharge at L1, L2 and L3; charge at L1 and discharge at either L2 or L3 as a smart scheme which prioritises battery discharge for V2G services; and charge at L2 or L3 while discharging at L1 which prioritises battery recharging for the next trip and minimises V2G the contribution to the grid.

Changing the charge/discharge rate had little impact on the daily energy throughput (119-123 Ah) because the battery was discharging by 30% only. Therefore, the battery degradation rate and associated costs were stable at 0.033-0.034% km^{-1} and £0.17-0.19 km^{-1} across the five charge/discharge combinations and illustrated in Figure 5a. In all cases, battery replacement was every 1.7 years which required positive hourly payments from the aggregator if costs were not to exceed that of a conventional vehicle, both over two years and the vehicle lifetime.

The charging level affected the number of vehicles required in the fleet to meet the 50 MW power and 15-minute duration requirements. The number of vehicles necessary to meet the power requirements decreased

[10]See `http://ukevse.org.uk/charge-points-chargers/` for a description of the three charging levels.

as charge/discharge rates increase from L1/L1 (44,300 vehicles for 0.42 h) to L2/L2 (32,300 vehicles for 0.25 h). Payments of at least £37 were required by existing EV owners, increasing to at least £52 for prospective owners under both L1/L1 and L2/L2, equivalent to at least 4,900 times what might be paid by the aggregator.

For L3/L3 charge/discharge rates, a fleet of 25,700 vehicles was sufficient to meet the power requirement. An additional 30,200 was needed to meet the duration requirement, shown as a yellow bar in Figure 5c at charging level 3. The total fleet at L3 charge/discharge rates met the ancillary service demands for 2.3 h. This long connection time led to the lowest hourly payments of £7 to existing EV owners and £9 for prospective owners. These low payments are illustrated by the smallest stacked bars in Figure 5d. The likely aggregator revenues were still exceeded by at least 280 times.

Fleet size and hourly payments from the aggregator were sensitive to the discharge rate under both smart charging schemes. The smart connection schemes favouring V2G services (L1/L2 and L1/L3) displayed the same fleet size and required hourly payments from the aggregator as under L2/L2 and L3/L3, respectively. Likewise, the smart connection scheme favouring battery charging (L2/L1 and L3/L1) yielded the same values as the L1/L1 case. Full results are given in Table **??**.

3.6. End-of-life criterion for batteries

Traditionally, batteries reach the end of their life with a 20% capacity fade. However, a better assessment of whether a battery is still fit for purpose is to consider its ability to satisfy driving needs. In this case, over half of all trips in the US were achieved even with a 70% battery capacity fade [**?**]. Therefore, the sensitivity of costs to end of life criterion, ranging from 20% to 70% in 10% intervals, was investigated.

Battery degradation fell linearly as the end of life criterion was relaxed from 20% to 70% capacity fade ($R^2 > 0.99$) from £0.17 km^{-1} to £0.14 km^{-1} as in Figure 6a. Likewise, net annual costs by 51% from £10,900 to £5,500 (Figure 6b) as the battery pack replacement frequency decreased from 1.7 years to 7.2 years over the same capacity fade range. EV fleet size to meet the 50 MW firm fast reserve power requirement increased linearly with a relaxation of end of life criterion ($R^2 > 0.82$). Fleet size was 44,300 for capacity fade up to 30%, 54,300 for capacity fade of 40-60% and 68,500 for a 70% capacity fade. An additional 18,700 EV, 63,700 EV and 80,400 EV were required to meet the firm fast reserve 15-minute duration requirement for capacity fades of 30%, 60% and 70%, respectively.

The smaller fleets (fewer than 100,000 vehicles) were connected for a median 0.42 h (0.33-0.58 h). Required hourly payments to the two EV owner groups decreased as a quadratic ($R^2 = 1$) with increasing (20%, 40% and 50%) capacity fade. The 18,700 EV required to meet the firm fast reserve duration requirement coincided with the longest connection time of 0.58 hours for a 30% capacity fade. The consequence of a large number of vehicles connecting for a long time was less burden per vehicle, leading to lower compensation payments. Here, the existing EV owner needed £6 per hour to recover battery degradation costs, while prospective EV owners would need £16 and £29 to be left no worse off than owning a conventional vehicle by the end of its lifetime or within two years, respectively.

Connection time increased to 2.7 hours and 2.3 hours for capacity fades of 60% and 70%, respectively. Total fleet sizes were now 118,000 EV and 149,000 EV, respectively. These much larger fleets connected for the longest times yielded the lowest hourly payments required across the scenarios investigated, illustrated using the smallest stacked bars in Figure 6d. Existing EV owners required less than £1 per hour to recover costs, while prospective EV owners would need up to £7 to be left no worse off than owning a conventional vehicle after two years. The gap between likely grid payments to the aggregator and the total disbursement to the fleets remained at least 20 times. Full results are given in Table **??**.

3.7. Comparisons across sensitivity analyses

Figure 7a, b and c illustrate the sensitivity of battery degradation costs, annual costs and hourly payments, respectively, to the six scenarios evaluated in this work. Battery degradation costs, net annual costs and hourly payments were each most sensitive (highest range of values) to the initial battery cost. After battery cost, both battery degradation costs and net annual costs were most sensitive to the battery capacity/AER. Hourly payments both to existing EV owners and prospective EV owners wishing to recover costs over the vehicle lifetime were most sensitive to charging level. Hourly payments to prospective EV owners to leave them no worse off than owning a conventional vehicle after the second year were most sensitive to battery capacity/AER. Battery degradation costs were most insensitive to charging level. Net annual costs were robust against both charging level and DOD. Hourly payments across all customer groups were most insensitive to charging regime.

Figure 8 illustrates the impact of connection time and battery degradation costs on hourly payments. In Figure 8a, hourly payments decrease as a power law with increasing connection time ($R^2 > 0.60$). Both connection time and total vehicle number, illustrated in Figure 8b and c, respectively, were most dependent on end of life capacity fade. Likewise, they were most insensitive to charging level (and independent of battery cost).

The UK fleet of EV grew by (a median) 23% annually from 1994 to 2013 [**?**][11]. Opportunistic charging with DOD to 80% required the smallest fleet of 23,400 EV to provide firm fast reserve. Opportunistic charging with end of life criterion relaxed to 70% required the largest fleet of 149,000 EV to meet firm fast reserve requirements. In the best case, such an EV fleet would be in service in the year 2019; in the worst case, by 2028 using the observed 23% annual growth compounded, as shown in black asterisks in Figure 9. This projection is optimistic because it relies on four assumptions: first, that the median growth rate

[11]This analysis is based in 2013 to maintain consistency across all inputs. Latest data shows 16,200 EV were sold in 2014. The influence of this jump in EV sales is to increase the median annual growth rate from 23% to 25%.

continues; second, all of the vehicle owners choose to participate in V2G; third, the large gaps between cost of ownership and rewards accrued from V2G participation are closed; and fourth, that no EV are retired from the fleet. Finally, achieving a fleet under these assumptions leads to firm fast reserve provided for a median 0.42 h, up to 2.7 h per day, starting at 1900h for both opportunistic and charging at home only and at 0930h when charging at work only. Therefore, the fleet must be larger still to increase the number and duration of connection periods to enable participation in an all-day, everyday ancillary services market. A recent survey of industry perspectives [**?**] echoes these findings, suggesting that V2G will be a long term prospect on account of the time required to achieve a large enough EV fleet, both to meet V2G grid requirements and justify the investment in infrastructure.

4. Conclusion

Often, it is suggested that the energy and capacity payments from providing V2G ancillary services can reduce EV ownership costs which acts as an incentive for prospective EV purchasers. This work has investigated this attractiveness to these consumer groups separately. On the one hand, the existing EV owner should receive payments to cover additional battery degradation costs associated with providing firm fast reserve over the vehicle lifetime. On the other, a prospective EV owner will be comparing costs to a conventional vehicle and will want to recover any excess within two years, in general.

An EV being driven on the NEDC and not participating in V2G has a battery lifetime of 12 years because the daily energy throughput is 0.93 Ah and battery state of charge does not drop below 98%. Providing firm fast reserve leads to daily discharges of 30% and energy throughout of 122 Ah. Therefore, battery life shortens to 1.7 years. The existing or prospective EV owner would be expected to meet the costs of battery replacement under traditional vehicle ownership models. A vehicle aggregator is required to pool vehicles to meet the UK National Grid firm fast reserve requirements of 50 MW for 15-minutes. In 2013, the aggregator would likely receive a capacity payment of £805 per hour the fleet was connected to the grid.

Across all scenarios, providing V2G ancillary services is unattractive to either existing or prospective EV owners. In most cases, the fleets are connected from 1900h for 0.42 hours, up to 2.7 hours. At most, the aggregator would receive £2,100. However, a minimum of 23,400 EV (DOD = 80%) are required to meet the firm fast reserve requirements, up to 149,000 EV when end of life criterion is relaxed to 70% capacity fade. Therefore, the aggregator may only have £0.004-0.034 to pay out to each vehicle based on its capacity payments from the grid. However, existing EV owners need hourly payments of at least £0.35 (end of life capacity fade criterion of 60%) up to £105 (battery costs of £800 kWh^{-1}) to recover the costs due to battery degradation to leave them no worse off than if they did not provide V2G services. Therefore, likely disbursements from the aggregator are 20-14,000 times lower than what each vehicle owner would need.

Similarly, prospective EV owners need at least £5 per hour (battery capacity of 12 kWh) up to £160 (battery costs of £800 kWh^{-1}) for the costs of owning an EV and providing V2G services to be no higher than those of a conventional vehicle after two years. Here, likely aggregator revenue is 270-27,000 times lower than necessary compensation to prospective EV. Relaxing the payback time from two years to the vehicle lifetime of eight years led to hourly payments of £2 (battery capacity of 12 kWh) to £135 (battery costs of £800 kWh^{-1}), equivalent to 110-17,800 times the likely aggregator receipts. Battery degradation costs, net annual costs and hourly payments to both EV customer groups were all most sensitive to battery cost. Battery degradation costs and net annual costs were most insensitive to charging level. Hourly payments for both EV owner groups were most insensitive to charging regime.

A large number of vehicles must be connected simultaneously to meet the power and duration requirements of firm fast reserve. The possibility of satisfying these through an aggregator will be held back by the low numbers of EV on the road in the UK. In the best case, it may be the end of this decade before there are enough EV in service to compete successfully to provide firm fast reserve. In the worst case, it may be closer to 2030 before cumulative EV sales are large enough. Both of these projections are based on the assumption that median growth rates in the UK EV fleet continue, that every EV owner participates in the aggregator and no EV leave the fleet. Even then, these represent the minimum fleet numbers and can only provide firm fast reserve for 0.42 h in the evening. The larger (worst case) fleet size is required to reduce the per vehicle capacity payment to minimise barriers to V2G cost effectiveness. Still, more growth in the fleet will be required to extend in number and duration the firm fast reserve periods so that EV can compete successfully in an all-day, every day ancillary services market. Consequently, V2G services are not cost-effective, thus not attractive, under current market and regulatory conditions and the assumptions used in this work. Therefore, while there may be reasons for encouraging EV uptake, V2G is unlikely to be one of them.

5. Acknowledgements

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Table 1: Specifications of Nissan LEAF used in the ADVISOR model

Glider mass (kg)	1175
Kerb mass (kg)	1538
Coefficient of drag	0.29
Frontal area (m^2)	2.27
Wheel diameter (m)	0.20
Peak motor power (kW)	80
Peak motor torque (Nm)	280
Energy use on the NEDC (Wh km^{-1})	150

List of tables

Table 2: Revenues and costs associated with operating an EV fleet which is providing firm fast reserve in the base case.

Base case	
Start time (h)	19
Hours available	0.42
Vehicle number (total)	44299
- power level	44299
- power duration	0
Revenues to the fleet aggregator	
Energy (£)	1753
Capacity (£)	335
Revenue available per vehicle (£)	0.008
Cost to each EV owner	
Battery degradation costs (£ km^{-1})	0.17
Annual net costs (£)	-10856
Battery lifetime (years)	1.7
Compensation required each EV owner to cover costs	
Hourly payments (£ h^{-1})	
- NPV EV with no V2G	37
- NPV conventional vehicle over lifetime	52
- NPV conventional vehicle by year 2	64

Figure captions

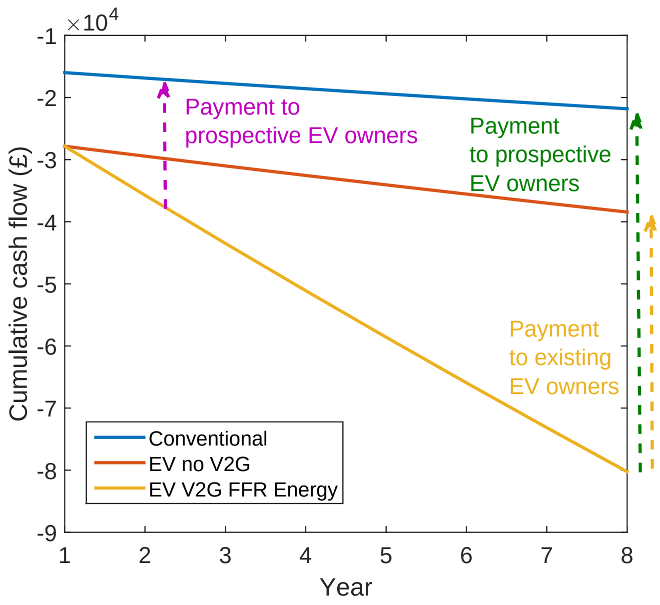
1. Schematic of revenue gap which needs to be filled by firm fast reserve capacity payments for a) the existing EV owner to be left no worse off than if there was no participation in V2G by the end of the vehicle lifetime (vertical arrow at year 8); the prospective EV owner to be left no worse off financially than the owner of a conventional vehicle (blue solid) after two years (purple arrow) by the end of the vehicle lifetime (green arrow). The EV with no V2G and providing firm fast reserve incorporating energy payments only is shown by a red solid and yellow solid lines, respectively.
2. Summary of the impact of AER on: a) battery degradation cost per km travelled; b) annual payments; c) total number of vehicles in the fleet required to meet the power (blue) and duration (yellow) requirements of firm fast reserve; and d) the hourly payments due to existing EV owners (blue), prospective EV owners wishing to recover costs over the vehicle lifetime (green) and prospective EV owners wishing to recover costs within two years (yellow).
3. Probability of the vehicle driving (blue, solid) or stationary and available to supply V2G services at work only (green, dashed) or at home only (black, dashed) in a 24-hour period.
4. Summary of the impact of individual vehicle battery DOD on: a) battery degradation cost per km travelled; b) annual payments; c) total number of vehicles in the fleet required to meet the power (blue) and duration (yellow) requirements of firm fast reserve; and d) the hourly payments due to existing EV owners (blue), prospective EV owners wishing to recover costs over the vehicle lifetime (green) and prospective EV owners wishing to recover costs within two years (yellow).
5. Summary of the impact of charging level on: a) battery degradation cost per km travelled; b) annual payments; c) total number of vehicles in the fleet required to meet the power (blue) and duration (yellow) requirements of firm fast reserve; and d) the hourly payments due to existing EV owners (blue), prospective EV owners wishing to recover costs over the vehicle lifetime (green) and prospective EV owners wishing to recover costs within two years (yellow). Key for charging levels: 1 = L1/L1; 2 = L2/L2; 3 = L3/L3; 4 = L1/L2; 5 = L1/L3; 6 = L2/L1; and 7 = L3/L1.
6. Summary of the impact of EOL criterion on: a) battery degradation cost per km travelled; b) annual payments; c) total number of vehicles in the fleet required to meet the power (blue) and duration (yellow) requirements of firm fast reserve; and d) the hourly payments due to existing EV owners (blue), prospective EV owners wishing to recover costs over the vehicle lifetime (green) and prospective EV owners wishing to recover costs within two years (yellow).
7. Summary plot of the range of sensitivities of a) battery degradation cost per km travelled; b) annual payments; c) hourly payments required by each EV; d) capacity payment gap for the EV for V2G ancillary services and across the sensitivity tests of: i. charging regime; ii. battery capacity and AER; iii. DOD for firm fast reserve; iv. battery cost; v. charging level; and vi. end of life criterion. For

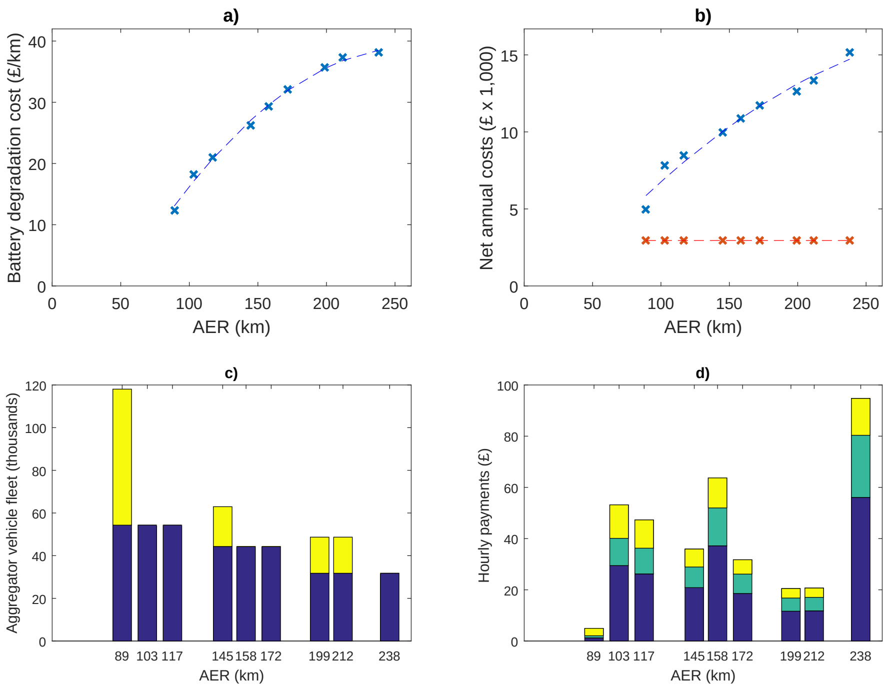
subplots c) and d): blue represents the two year time horizon; red, the asset life; and yellow, the gap between lifetime costs of an EV with and without participation in firm fast reserve.

8. Comparison of hourly payments to the individual vehicles with required fleet size to meet firm fast reserve requirements of 50 MW for 15-minutes. a) hourly payments per vehicle as a function of connection time, where bubble size is proportion to total vehicle fleet number; b) summary plot of the range of sensitivities of connection time by sensitivity test; and c) summary plot of the range of sensitivities of total fleet number by sensitivity test. Blue, yellow and red series in a) represent hourly payments to existing EV owners, to prospective EV owners over the vehicle lifetime and within two years, respectively.

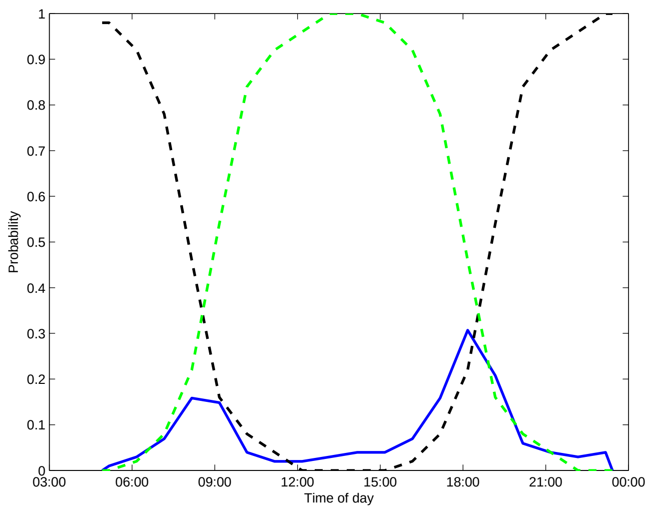
9. EV sales in the UK from 1994 to 2013 (blue) and projection sales using median growth rate compounded annually (orange). Black asterisks indicate the years in which the smallest and largest electric vehicle fleet size is achieved: 2019 for the best case of 23,400; and 2028 for the worst case of 149,000.

List of figures

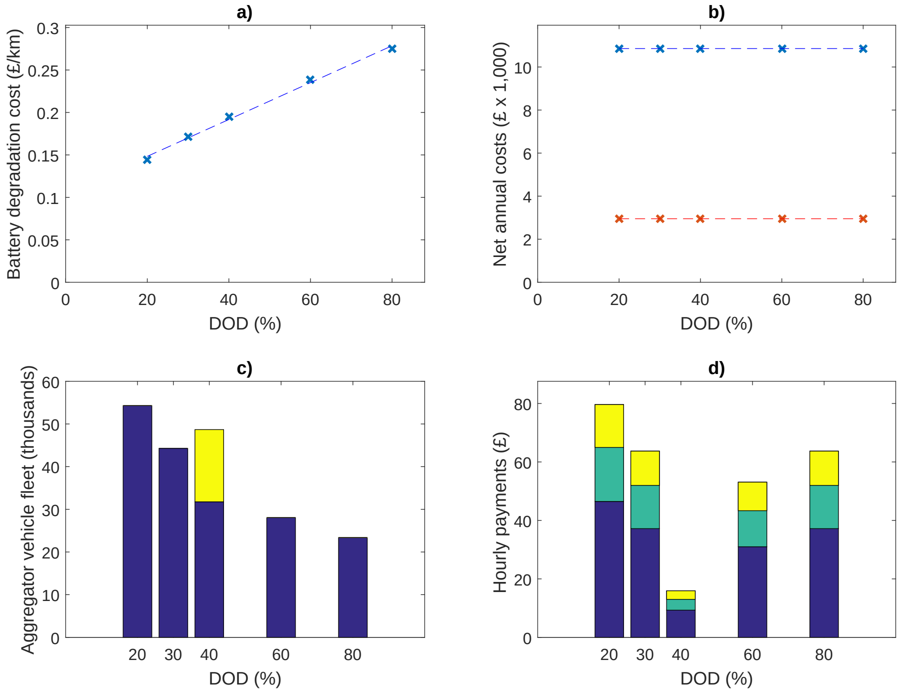


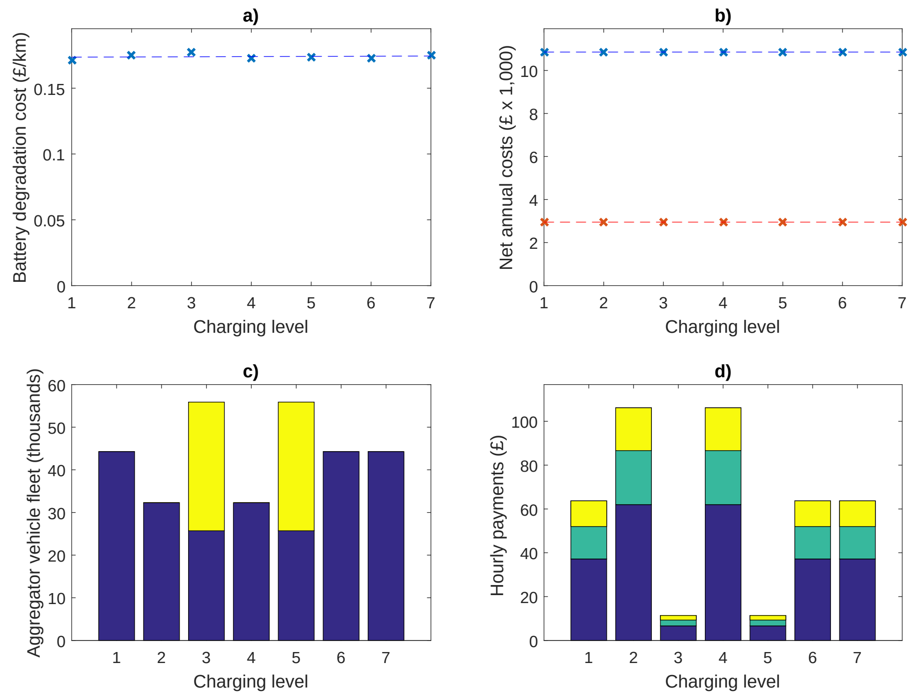


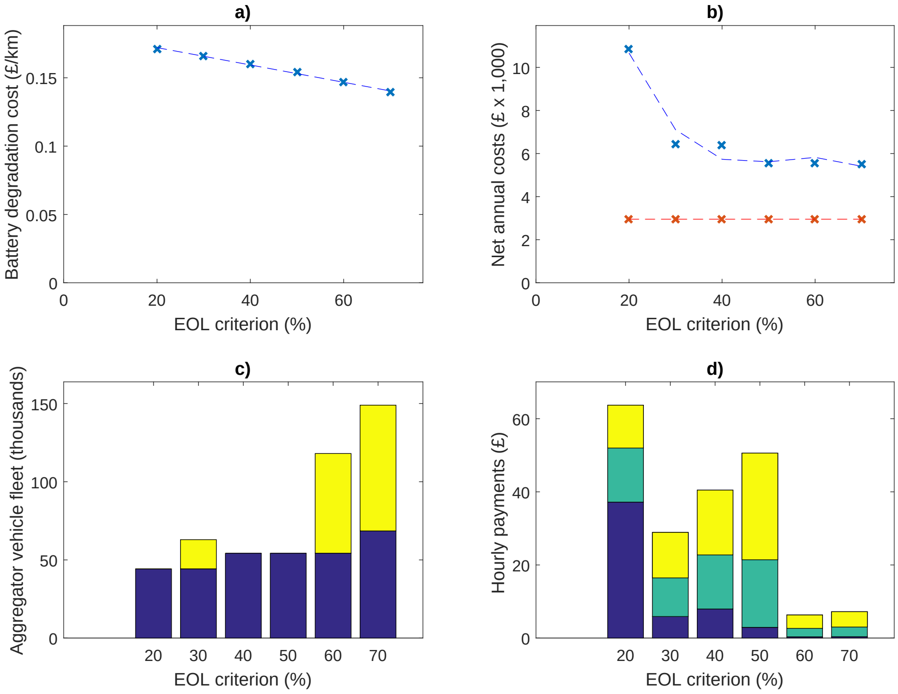
a)
Battery degradation cost (£/km)
AER (km)
b)
Net annual costs (£ x 1,000)
AER (km)
c)
Aggregator vehicle fleet (thousands)
AER (km)
d)
Hourly payments (£)
AER (km)



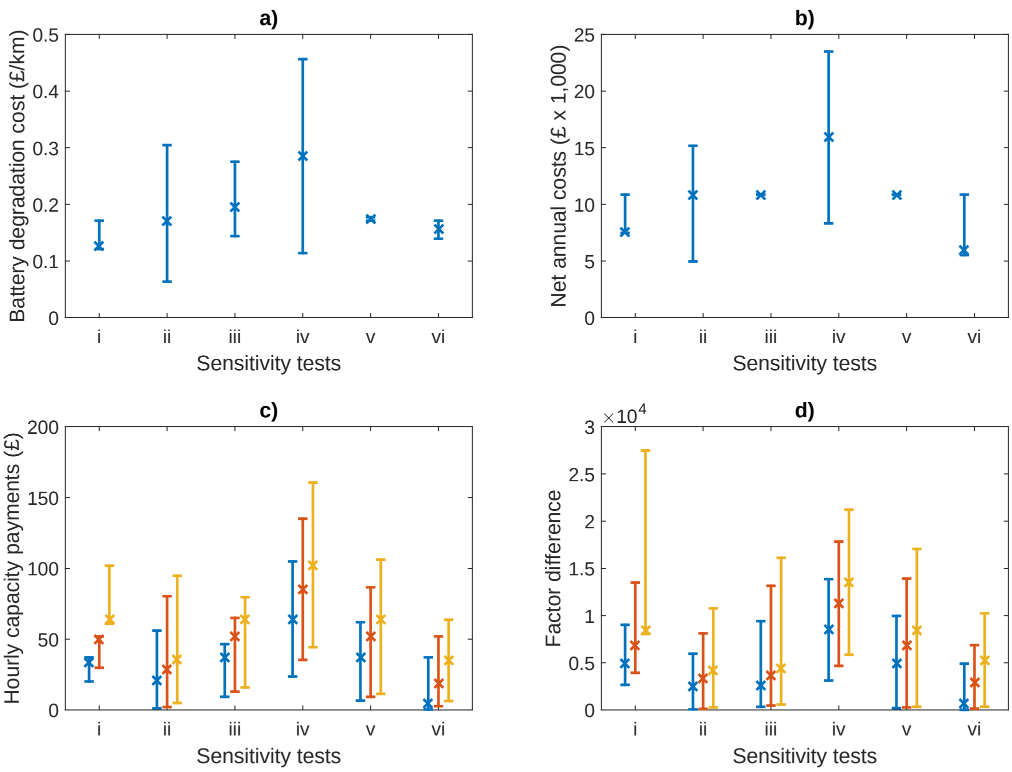
Probability
Time of day

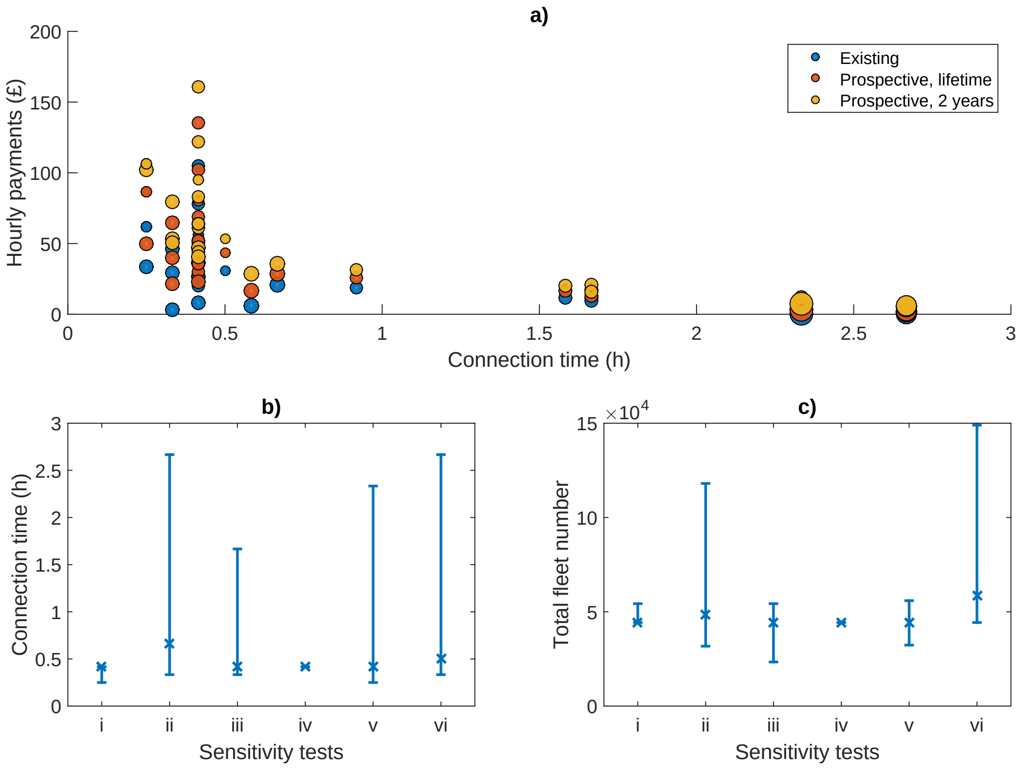

a)
Battery degradation cost (£/km)
0
0.05
0.1
0.15
0.2
0.25
0.3
0
20
40
60
80
DOD (%)
b)
Net annual costs (£ x 1,000)
0
2
4
6
8
10
0
20
40
60
80
DOD (%)
c)
Aggregator vehicle fleet (thousands)
0
10
20
30
40
50
60
20
30
40
60
80
DOD (%)
d)
Hourly payments (£)
0
20
40
60
80
20
30
40
60
80
DOD (%)


a)
Battery degradation cost (£/km)
0
0.05
0.1
0.15
1
2
3
4
5
6
7
Charging level
b)
Net annual costs (£ x 1,000)
0
2
4
6
8
10
1
2
3
4
5
6
7
Charging level
c)
Aggregator vehicle fleet (thousands)
0
10
20
30
40
50
60
1
2
3
4
5
6
7
Charging level
d)
Hourly payments (£)
0
20
40
60
80
100
1
2
3
4
5
6
7
Charging level



Appendix A. Supplementary tables of results


a)
Battery degradation cost (£/km)
Sensitivity tests
b)
Net annual costs (£ x 1,000)
Sensitivity tests
c)
Hourly capacity payments (£)
Sensitivity tests
d)
Factor difference
×10^4
Sensitivity tests
i
ii
iii
iv
v
vi


a)
Existing
Prospective, lifetime
Prospective, 2 years
Hourly payments (£)
Connection time (h)
b)
Connection time (h)
Sensitivity tests
i
ii
iii
iv
v
vi
c)
$\times 10^4$
Total fleet number
Sensitivity tests

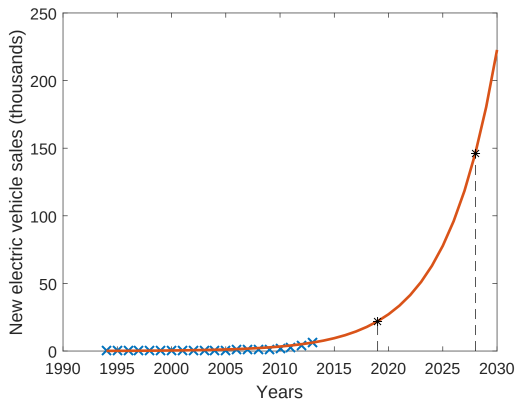

New electric vehicle sales (thousands)
Years

Table A.3: Revenues and costs associated with operating an EV fleet which is providing firm fast reserve by charging opportunistically and across all-electric ranges from 89 km to 238 km.

All-electric range (km)	89	103	117	145	158	172	199	212	238
Battery capacity (kWh)	12	16	18	21	24	26	30	32	36
Start time (h)	0830	1900	1900	1900	1900	1900	1900	1900	2000
Hours available	2.67	0.33	0.42	0.67	0.42	0.92	1.58	1.67	0.42
Vehicle number (total)	118041	54302	54302	62951	44299	44299	48678	48678	31762
- power level	54302	54302	54302	44299	44299	44299	31762	31762	31762
- power duration	63739	0	0	18652	0	0	16916	16916	0
Revenues to the fleet aggregator									
Energy (£)	553	811	955	1511	1753	1979	3259	3535	4645
Capacity (£)	2147	268	335	537	335	738	1275	1342	335
Revenue available per vehicle (£)	0.018	0.005	0.006	0.009	0.008	0.017	0.026	0.028	0.011
Cost to each EV owner									
Battery degradation costs (£ km^{-1})	0.06	0.1	0.11	0.15	0.17	0.19	0.23	0.25	0.27
Annual net costs (£)	-4957	-7830	-8464	-9985	-10856	-11695	-12651	-13321	-15170
Battery lifetime (years)	2.3	2	1.9	1.8	1.7	1.6	1.5	1.5	1.4
Compensation required each EV owner to cover costs									
Hourly payments (£ h^{-1})									
- NPV EV with no V2G	1	29	26	21	37	19	12	12	56
- NPV conventional vehicle over lifetime	2	40	36	29	52	26	17	17	80
- NPV conventional vehicle by year 2	5	53	47	36	64	32	20	21	95

Table A.4: Revenues and costs associated with operating an EV fleet which is providing firm fast reserve by charging opportunistically, at home only and at work only.

Charging regime	Opportunistic	Home only	Work only
Start time (h)	1900	1900	0930
Hours available	0.42	0.42	0.25
Vehicle number (total)	44299	44299	54302
- power level	44299	44299	54302
- power duration	0	0	0
Revenues to the fleet aggregator			
Energy (£)	1753	1091	1180
Capacity (£)	335	335	201
Revenue available per vehicle (£)	0.008	0.008	0.004
Cost to each EV owner			
Battery degradation costs (£ km^{-1})	0.17	0.12	0.13
Annual net costs (£)	-10856	-7484	-7517
Battery lifetime (years)	1.7	2.4	2.3
Compensation required each EV owner to cover costs			
Hourly payments (£ h^{-1})			
- NPV EV with no V2G	37	20	33
- NPV conventional vehicle over lifetime	52	30	50
- NPV conventional vehicle by year 2	64	61	102

Table A.5: Revenues and costs associated with operating an EV fleet which is providing firm fast reserve by charging opportunistically and across a 20-80% range of depth of discharges.

Depth of discharge (%)	20	30	40	60	80
Start time (h)	1900	1900	1900	2000	2000
Hours available	0.33	0.42	1.67	0.5	0.42
Vehicle number (total)	54302	44299	48678	28057	23381
- power level	54302	44299	31762	28057	23381
- power duration	0	0	16916	0	0
Revenues to the fleet aggregator					
Energy (£)	1753	1753	1753	1753	1753
Capacity (£)	268	335	1342	403	335
Revenue available per vehicle (£)	0.005	0.008	0.028	0.014	0.014
Cost to each EV owner					
Battery degradation costs (£ km^{-1})	0.14	0.17	0.2	0.24	0.28
Annual net costs (£)	-10856	-10856	-10856	-10856	-10856
Battery lifetime (years)	2	1.7	1.5	1.2	1
Compensation required each EV owner to cover costs					
Hourly payments (£ h^{-1})					
- NPV EV with no V2G	46	37	9	31	37
- NPV conventional vehicle over lifetime	65	52	13	43	52
- NPV conventional vehicle by year 2	80	64	16	53	64

Table A.6: Revenues and costs associated with operating an EV fleet which is providing firm fast reserve by charging opportunistically and across a £200-800 kWh^{-1} range of battery costs.

Battery cost (£ kWh^{-1})	200	400	600	800
Start time (h)	1900	1900	1900	1900
Hours available	0.42	0.42	0.42	0.42
Vehicle number (total)	44299	44299	44299	44299
- power level	44299	44299	44299	44299
- power duration	0	0	0	0
Revenues to the fleet aggregator				
Energy (£)	1753	1753	1753	1753
Capacity (£)	335	335	335	335
Revenue available per vehicle (£)	0.008	0.008	0.008	0.008
Cost to each EV owner				
Battery degradation costs (£ km^{-1})	0.11	0.23	0.34	0.45
Annual net costs (£)	-8329	-13382	-18434	-23487
Battery lifetime (years)	1.7	1.7	1.7	1.7
Compensation required each EV owner to cover costs				
Hourly payments (£ h^{-1})				
- NPV EV with no V2G	24	51	78	105
- NPV conventional vehicle over lifetime	35	69	102	135
- NPV conventional vehicle by year 2	44	83	122	161

Table A.7: Revenues and costs associated with operating an EV fleet which is providing firm fast reserve by charging opportunistically and across a range of charging levels and combinations, from L1 to L3

Charging level	L1	L2	L3	L1 c, L2 d	L1 c, L3 d	L2 c, L1 d	L3 c, L1 d
Start time (h)	1900	1900	0830	1900	0830	1900	1900
Hours available	0.42	0.25	2.33	0.25	2.33	0.42	0.42
Vehicle number (total)	44299	32323	55884	32323	55890	44299	44299
- power level	44299	32323	25708	32323	25711	44299	44299
- power duration	0	0	30176	0	30179	0	0
Revenues to the fleet aggregator							
Energy (£)	1753	1753	1753	1753	1753	1753	1753
Capacity (£)	335	201	1878	201	1878	335	335
Revenue available per vehicle (£)	0.008	0.006	0.034	0.006	0.034	0.008	0.008
Cost to each EV owner							
Battery degradation costs (£ km^{-1})	0.17	0.17	0.18	0.17	0.17	0.17	0.17
Annual net costs (£)	-10856	-10856	-10856	-10856	-10856	-10856	-10856
Battery lifetime (years)	1.7	1.6	1.6	1.7	1.7	1.7	1.6
Compensation required each EV owner to cover costs							
Hourly payments (£ h^{-1})							
- NPV EV with no V2G	37	62	7	62	7	37	37
- NPV conventional vehicle over lifetime	52	87	9	87	9	52	52
- NPV conventional vehicle by year 2	64	106	11	106	11	64	64

Table A.8: Revenues and costs associated with operating an EV fleet which is providing firm fast reserve by charging opportunistically and across a 20-70% range of end of life capacity fade criteria.

End of life capacity fade criterion (%)	20	30	40	50	60	70
Start time (h)	1900	1900	1900	1900	0830	0830
Hours available	0.42	0.58	0.42	0.33	2.67	2.33
Vehicle number (total)	44299	62951	54302	54302	118041	148963
- power level	44299	44299	54302	54302	54302	68527
- power duration	0	18652	0	0	63739	80436
Revenues to the fleet aggregator						
Energy (£)	1753	1753	1753	1753	1753	1753
Capacity (£)	335	470	335	268	2147	1878
Revenue available per vehicle (£)	0.008	0.007	0.006	0.005	0.018	0.013
Cost to each EV owner						
Battery degradation costs (£ km^{-1})	0.17	0.17	0.16	0.16	0.15	0.14
Annual net costs (£)	-10856	-6456	-6410	-5557	-5542	-5526
Battery lifetime (years)	1.7	2.6	3.6	4.7	5.9	7.2
Compensation required each EV owner to cover costs						
Hourly payments (£ h^{-1})						
- NPV EV with no V2G	37	6	8	3	0.35	0.38
- NPV conventional vehicle over lifetime	52	16	23	21	3	3
- NPV conventional vehicle by year 2	64	29	40	51	6	7