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ECONOMIC ASSESSMENT OF USING ELECTRIC VEHICLES AND BATTERIES AS DOMESTIC STORAGE UNITS IN THE UNITED KINGDOM

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Increasing residential renewable energy generation and the consumers' demand for reducing their electricity bills leads to new opportunities to use electric vehicles (EVs) and batteries as domestic storage units. This paper assesses the economic feasibility of Vehicle-to-Home (V2H) and domestic battery systems in the United Kingdom (UK). To do the analysis, a UK average EV and domestic battery have been established; called UKEV and UKBat respectively. The UKEV characteristics were determined by taking a weighted average from the five highest selling EVs in the UK. An arithmetic mean was used for the individual UKBat features based on seven models currently available on the UK market. The UKEV and UKBat were compared under four scenarios. These are Ofgem's two domestic electricity profile classes (PC1, PC2) and two existing time-of-use tariffs; one with two and the other with three rates during a day. Maximum annual saving for the consumer was estimated to be around 35% and 57% per annual electricity bill for the EV and battery, respectively. On average, for both UKEV and UKBat, the three-rate tariff yielded 30% more savings than the two-rate tariff. Battery degradation cost was the major parameter affecting the economic feasibility of V2H and domestic batteries, but these costs are expected to continue to fall. Suitable time-of-use tariff design is the key to maximising consumers' savings in using these units.

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Keywords	electric vehicles; battery; vehicle-to-home systems; tariffs
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Abstract *Increasing residential renewable energy generation and the consumers' demand for reducing their electricity bills leads to new opportunities to use electric vehicles (EVs) and batteries as domestic storage units. This paper assesses the economic feasibility of Vehicle-to-Home (V2H) and domestic battery systems in the United Kingdom (UK). To do the analysis, a UK average EV and domestic battery have been established; called UKEV and UKBat respectively. The UKEV characteristics were determined by taking a weighted average from the five highest selling EVs in the UK. An arithmetic mean was used for the individual UKBat features based on seven models currently available on the UK market. The UKEV and UKBat were compared under four scenarios. These are Ofgem's two domestic electricity profile classes (PC1, PC2) and two existing time-of-use tariffs; one with two and the other with three rates during a day. Maximum annual saving for the consumer was estimated to be around 35% and 57% per annual electricity bill for the EV and battery, respectively. On average, for both UKEV and UKBat, the three-rate tariff yielded 30% more savings than the two-rate tariff. Battery degradation cost was the major parameter affecting the economic feasibility of V2H and domestic batteries, but these costs are expected to continue to fall. Suitable time-of-use tariff design is the key to maximising consumers' savings in using these units.*

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1. Introduction

Distributed energy resources are becoming increasingly prevalent, especially in developed countries, as an "energy transition" is underway from conventional fossil fuels, towards renewable sources of energy. The most mature and predominant technologies with the highest growth rates in the renewable sector are solar photovoltaics (PV) and wind. Both have from intermittency issues, and the question of large scale short and long-term electricity storage continues to grow as efforts towards decarbonising grids are made. Simultaneously, the transport sector, especially automotive, is seeing a shift towards Electric Vehicles (EVs)[1]. Although the clear winner between battery and hydrogen fuel cell is yet to be established, for grid applications in particular, lithium-ion battery electric vehicles (BEVs) currently dominate the market. The global stock of BEVs and PHEVs reached 3.1 million in 2017, compared to 7,200 FCEVs (IEA, 2018, p. 20).

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[1] Generally, the umbrella term EV is used to refer to BEVs, HEVs and PHEVs. In this paper the focus will lie on pure battery powered electric vehicles, BEVs and after the introduction when EV is used, it can be assumed to be synonymous for BEV.
FCEVs are hydrogen powered and they convert hydrogen to electricity through the fuel cell and are not of interest as batteries which are studied here.
ULEVs are a UK government specific term and can include any vehicle with tailpipe emissions below 75g CO2 per km travelled.

Out of these trends, a whole new area of prospective technologies known as Vehicle-to-Grid (V2G) arises. Using EVs and their batteries as storage devices could be used in frequency response and help the grid by alleviating the intermittency issue, meanwhile providing ancillary services and load shifting. However, this view taken from the systemic standpoint fails to consider the consumer.

Initially belittled by the traditional automotive industry, EVs have been taken increasingly more seriously since Tesla's success with the Model S. As of May 2018, 64 plug-in EV models[2] are available in the United Kingdom (UK), around 150,000 EVs have been registered and demand continues to grow (DfT, 2018a). EVs made up 1.7% of total vehicle registrations in 2017, up from 0.3% in 2013. The market share of EVs has grown by 0.32% per year, and total EV sales have increased 90% per annum between 2013-2017 (DfT, 2018b). On top of that, the UK government has announced the ban of the sale of new petrol and diesel internal combustion engine (ICE) cars from 2040 onwards (DEFRA and DfT, 2017). By 2040, Bloomberg New Energy Finance (BNEF) predict that 33% of the global car fleet will be EVs, and predominantly BEVs (BNEF, 2018a).

Alternative uses may be investigated to optimise battery usage, and value for money for the owner. Even if this is not the case, replacing batteries may be viable as battery prices continue to fall as the technology improves. In 2018, lithium-ion battery prices were down 79% compared to 2010, and are expected to fall a further 67% from today by 2030 (BNEF, 2018b). The closest related use for an EV owner would be Vehicle-to-Home (V2H), where the EV battery is used for domestic electricity storage. This way electricity bought in off-peak periods could be used during peak hours to save money on energy bills.

Simultaneously, the way electricity is generated, distributed and consumed is changing (UKPN, 2017). Renewables are growing more as wind and PV are becoming competitive energy sources (BNEF, 2018c). The UK grid is transforming away from fossil fuels towards low carbon sources of electricity. The share of generation from renewables was 29.3%, and only topped by gas with 40.4% in 2017 (DUKES, 2018). A further 20.8% came from nuclear, and coal has been almost phased out entirely, comprising only 6.7% of generation in 2017, down from 9% in 2016 and 22% in 2015 (DUKES, 2018). Furthermore, total and peak demand is forecasted to grow over the coming decades as more energy in the form of electricity will be required for EVs and heating (UKPN, 2017). Due to rapid PV uptake the capacity gap is getting worse, especially in places such as California and Australia where solar irradiation is high (Küfeoğlu and Pollitt, 2018).

The main purpose of buying an EV is mobility. Storing energy will be a secondary benefit to the EV owners. Whereas, domestic battery units are bought for energy storage only. These home battery systems can achieve almost all benefits that the V2H concept promises for households. Therefore, the problem statement behind this study is; in economic terms, which one, home battery systems of EVs used as V2H, makes more sense from a home owner's perspective in the UK?

The main aim of this paper is to determine whether using an EV or a home battery for domestic electricity storage is economically preferable from a residential customer's perspective. Furthermore, this project aims to present findings from UK as a case study, which can be studied later on for larger

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[2] This includes Plug-in Hybrid Electric Vehicles (PHEVs) and BEVs as these vehicle groups have batteries that can be charged directly from a plug.

customer groups in Europe, as well as in the rest of the world. To achieve these aims the following objectives must be met:

- Consider the potential and future of EVs and home battery systems
- Find an a current average EV and home battery in the UK market
- Highlight consumer behaviour with electricity and EV use
- Compare the average EV and home battery on an economic basis
- Evaluate policy options to introduce more suitable tariff options to facilitate V2H or batteries as domestic electricity storage devices.

To do the analysis, we need to have a typical EV and a typical home battery unit with certain ratings and properties. Instead of using completely hypothetical models, we decided to define two products which will have similar technical properties to the ones available in the UK market. As a result, we introduced a typical EV, UKEV, whose characteristics were determined by taking a weighted average from the five highest selling EVs in the UK. Similarly, to carry out the analysis, we introduced UKBat, a home battery unit which is defined by taking the arithmetic mean from seven models available in the UK market.

1.1 Vehicle-to-Home (V2H)

Combining the three trends of increased EV uptake, EV batteries performing better than expected and a shift towards renewable sources in generation has led to research focusing on V2G concepts and technologies. Nonetheless, less effort has been dedicated to the relatively more novel concept of V2H, resulting in less academic literature on the topic. Within V2H, many have focused on coupling domestic electricity storage with renewable installations, such as a system with an EV and PV (Hasegawa et al., 2017), or a home battery and PV (Uddin et al., 2017a). Other studies have focused on net zero energy buildings, looking more at reducing electricity requirements over the economic aspects (Alirezaei et al., 2016; Doroudchi et al., 2018). However, Doroudchi et al. determined that storage is very much dependent on local electricity prices, and much more feasible where these prices are higher.

V2H can also be regarded as a stepping stone towards more advanced EV to electricity technologies such as Vehicle-to-Business (V2B), Vehicle-to-Vehicle (V2V) and V2G. V2H is simpler as it requires the least infrastructure and no legislative changes (Liu et al., 2013). Advantages of V2H and domestic battery systems include improved self-sufficiency, safety from black-outs, less effect by demand side management measures such as peak pricing, lower electricity bills and selling electricity back to the grid (Garcia-Villalobos et al., 2015; Liu et al., 2013).

2. UK EV and V2H studies

This section looks at real life studies that have taken place or are taking place within the context of EVs in the UK or V2H elsewhere. Firstly, we will outline the EV deployment study in the UK by Low Carbon London and UK Power Networks. And then we will summarize two V2H studies from Japan and Spain in Table 1.

The Low Carbon London Learning Lab's report on the Impact and Opportunities for the wide-scale EV deployment carried out the largest study on EV charging behaviour in the residential, commercial and public domain at the time of the report (Aunedi et al., 2014). Findings of significance are that 84% of charging events for residential and commercial users occur at home or at office charging points. This means that public charging stations are only used for back-up charging events or when users have no alternative. It also points to the short distances driven by EV users, with a median of 3.5 km and 95% of all trips shorter than 25 km (Aunedi et al., 2014, p. 49).

On average, residential users were found to have a daily charging demand of 3.5kWh, equating to a daily driving distance of 17.5 km (Aunedi et al., 2014, p. 20). This indicates that the remaining state of charge (SoC) in the batteries is sufficient on most days for V2H or some V2G functionality since the battery capacities of EVs range from 20 kWh to 100 kWh. The study also supports smart EV charging, as uncontrolled charging was shown to increase the load on the system during peak hours whereas shifting these loads to later in the night would help balance the demand curve.

Table 1

Summary of two V2H studies from Japan and Spain

Country	**Trial / product**	**Concept and value proposition**	**V2H output (kW)**	**capacity (kWh)**	**Cost of V2H system**	**Savings**
Japan	Leaf to Home (Nissan, 2012; Nissan, 2017)	power to homes during emergencies and natural disasters, peak demand reduction, improved grid stability	6	24	330,000 Yen (£2,307)[3]	By using six Leafs, energy consumption of a business was reduced by 2.5%, saving 500,000 Yen (£3,496) annually (Alliance, 2013)
Spain	Canary Islands case study (Colmenar-Santos et al., 2017)	peak demand reduction, improved grid stability	3	24	3,000 € (£2,712)	Annually up to around 600€ (£542) of savings per V2H use

It is of great interest to EV owners in the UK to know about the economic potential of this technology. A Canadian residential V2H study found that a 28 kWh EV battery's life expectancy while driving 50 km per day was decreased from 10.6 to 10.2 years with one hour of daily V2H use. This decreased further to 8.5 years with eight hours of V2H use per day (Darcovich et al., 2017). Hence, the inclusion of battery degradation costs is fundamental to allow for an accurate cost calculation, and the comparison against domestic battery systems will allow consumers to make better informed purchasing decisions.

3. Methodology

This chapter outlines the methodology used in this study. The key steps necessary to complete the analysis for the domestic storage systems are as follows:

1. Determine the average EV (UKEV) and battery (UKBat) in the UK.

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[3] According to currency exchange rates in September 2018.

2. Establish the scenarios for evaluation, including domestic profile classes, tariff structures and battery degradation rates.
3. Analyse EV customer behaviour.
4. Evaluate the performance of UKEV and UKBat in all scenarios.

For step one, a weighted average from the five most registered new EVs over the past five years in the UK will be used to determine the average EV. If possible, the average battery will be determined in the same manner. However, alternatively, if sales or registration data are unavailable, a simple arithmetic mean will be used to determine the UK average home battery system from the home batteries that have the highest availability

For step two, two domestic profile classes PC1 and PC2 (regular and Economy 7)[4] will be used in conjunction with two time-of-use tariffs that currently exist in the UK. In addition to this, battery degradation rates will be determined at four levels (none, low, medium, high) from the academic and grey literature, in conjunction with real data and manufacturer information.

Step three will require the analysis of EV user behaviour to determine during which hours the EV is at home and can be used for V2H functionality, i.e. an arrival and leaving time for week and weekends is required. In addition to that, the remaining SoC at arrival must be known to confirm that there is sufficient amount of energy for V2H usage.

Finally, step four will analyse both options in terms of their economic feasibility for their potential as domestic batteries using both domestic profile classes with the existing two-rate and three-rate tariff system. In addition, four battery degradation rates will be used, yielding a total of sixteen different scenarios. Table 2 shows the parameters of the formulae used in the analysis process.

Table 2

Parameters used for the savings calculation potential of step four.

Parameter	Short	Unit
Net electricity shifted from peak to off-peak	ΔE	kWh
Price difference between peak and off-peak tariff	Δp	£/kWh
Peak electricity rate	p_p	£/kWh
Off-peak electricity rate	p_o	£/kWh
Medium electricity rate (three-rate tariff only)	p_m	£/kWh
Round-trip efficiency	η_{rt}	%
Charging efficiency	η_c	%
Discharging efficiency	η_d	%
Energy-related degradation	D_e	£/kWh
Power-related degradation	D_p	£/kWh^2
Saving	S	£

The starting point to determine a formula to calculate the financial incentive to use an EV or home battery for shifting consumption away from peak hours.

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[4] Profile Class 1 (PC1) are regular customers with flat tariffs, whereas Profile Class 2 (PC2) are customers with Economy 7 meters. The medium consumers of PC1 consume 3,100 kWh annually, whereas PC2 consume 4,200 kWh annually (Ofgem, 2017a).

Therefore, total net savings will be calculated as the difference between savings through shifting electricity from peak to off-peak hours and costs, represented by battery degradation effects, seen in (1).

$$Net\ Savings = Savings - Costs \tag{1}$$

The savings are calculated as the product of total consumption in kWh shifted (ΔE) and the price difference between peak and off-peak rates (Δp) divided by the round-trip efficiency of the battery being charged and discharged (η_{rt}). The costs are the sum of energy and power-related degradation costs to the battery, following Bashash et al. and Schuller et al. (Bashash et al., 2011; Schuller et al., 2014).

Energy-related degradation in £/kWh (D_e) is linear as increased energy throughput causes more degradation. It is multiplied out by total consumption shifted (ΔE) to give costs in monetary terms. Power-related degradation in £/kWh^2 (D_p) is quadratic as high charging power causes increased battery degradation. It is multiplied out by total consumption shifted squared (ΔE^2) to give costs in monetary terms. Combining these savings and costs gives the formula seen in (2).

$$S = \left(\frac{\Delta E \cdot \Delta p}{\eta_{rt}}\right) - (D_e \cdot \Delta E + D_p \cdot \Delta E^2) \tag{2}$$

Within (3), the price difference (Δp) and round-trip efficiency (η_{rt}) are calculated from (3) and (4).

$$\Delta p = p_p - p_o \tag{3}$$

$$\eta_{rt} = \eta_c \eta_d \tag{4}$$

For the three-rate tariff calculation (2) expands to (5) to account for the additional third time-of-use rate. This means that on the saving side ΔE is broken down into ΔE_1 and ΔE_2. ΔE_1 is the electricity shifted from the peak to off-peak tariff. ΔE_2 is the amount of electricity shifted from medium (normal day rate outside night and penal period) to off-peak tariff. Nothing changes in terms of costs compared to (2), as the battery degradation is not affected by tariff price differences but only by the amount of electricity put through the battery.

$$S = \left(\frac{\Delta E_1 \cdot \Delta p + \Delta E_2 \cdot \Delta p_2}{\eta_{rt}}\right) - (D_e \cdot \Delta E + D_p \cdot \Delta E^2) \tag{5}$$

Within (5) the new terms on the saving side, the amount of electricity shifted from medium to off-peak tariff (ΔE_2) and the price difference between medium and off-peak tariff (Δp_2) are calculated from (6) and (7).

$$\Delta E_2 = \Delta E - \Delta E_1 \tag{6}$$

$$\Delta p_2 = p_m - p_o \tag{7}$$

4. Average EV and Battery in the UK

This chapter outlines how the average EV and battery in the UK have been determined for the use of this paper. They will be referred to as UKEV and UKBat respectively.

4.1 UKEV

According to the Department for Transport, over the past five years, the five most registered EVs in the UK were the Nissan Leaf, BMW i3, Tesla Model S, Renault Zoe and Tesla Model X (DfT, 2018b). Only EVs were considered when taking the average of the characteristics of the EVs, whereas PHEVs operate at a smaller scale in terms of batteries and compete in a slightly different market. The Tesla Model 3 has not been included, as UK delivery is yet to commence and the Chevrolet Bolt EV is sold in Europe as Opel Ampera-E, but is not available as right-hand drive in the UK (Donath, 2016). After determining the five most registered EVs in the UK market, data were collected on battery power, capacity range and cost. Table 3 summarises some of the features of the five most popular EVs in UK. For each of the five models, the two most popular battery sizes and respective values are shown. Battery power is given in kW and battery capacity in kWh are given from manufacturer datasheets.

The US-based Environmental Protection Agency (EPA) five-cycle range was chosen as a more realistic measure of range over the New European Driving Cycle (NEDC), which delivers significantly higher values. However, EPA values are still ambitious and not always achieved under real driving conditions. Range varies with temperature, driving type and speed.

The UK on-the-road (OTR) price for the vehicles was determined from an EV database, which factors in VAT, government incentives (£4,500 plug-in grant for the UK), vehicle registration fee, first year Vehicle Excise Duty (VED), number plates and delivery (EVDB, 2018). These are base model costs without any extras, and thus represent a low range estimate of the real price people pay for these vehicles on average.

The arithmetic mean was taken for each vehicle across the six characteristics, and then weighted depending on total sales of the model over the past five years. The five models were weighted at 43.8%, 21.3%, 16.4%, 13.5% and 5.0% respectively.

Table 3
Core data of five most popular EVs in the UK. For each model, the two most popular versions in terms of total sales were chosen and are compared here.

Model	**Power (kW)**	**Capacity (kWh)**	**EPA Range (km)**	**OTR Cost (£)**
Nissan Leaf[5]	80	24/30	135/172	21,680/25,790
BMW i3	125	22/33	130/183	27,830/29,570
Tesla Model S 75D/90D	245/311	75/90	417/473	66,050/87,050
Renault Zoe R90[6]	65/66	22/41	156/260	19,845/23,770
Tesla Model X 75D/100D	245/311	75/100	383/475	71,350/88,050

The outcome of this weighting results in an EV with similar power characteristic to the BMW i3 with 130 kW power, a battery comparable to that of the larger Renault Zoe with 39.8 kWh battery and range of 223 km, while costing relatively more at approximately £36,000. This comparatively high price is due to the impact of the Tesla S and X, as these are far more expensive than the other three models under consideration. Table 4 summarizes the features of the hypothetical UKEV model.

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[5] A 40kWh model for the Leaf has become available in 2018 but it is excluded as the years assessed are 2013-2017.

[6] Renault offers the Zoe without the outright purchase of the battery but instead, with a leasing model where customers pay a monthly fee depending on annual mileage starting from £49 for the 22 kWh and £59 for the 44 kWh model. The prices shown here are of the models with battery lease, as these are much more popular. The new models all include a 41 kWh battery

Table 4

Characteristics of the average UK EV, called UKEV. The usable capacity was taken to be 90% Depth of Discharge (DoD) of the original capacity and consumption was calculated as capacity over range (Schuller et al., 2014).

Characteristic	**UKEV**
Power (kW)	130
Capacity (kWh)	39.8
Usable Capacity (kWh)	35.9
EPA Range (km)	223
Consumption (kWh/km)	0.179
OTR Cost (£)	35,986

4.2 UKBat

It is rather difficult to identify UK specific sales or registration data of home battery systems. Therefore, the popularity of models was determined through a comparison of popularity across various, independent battery installers and review guides (EcoExperts, 2018; Ingrams, 2017; Naked Solar, 2018; Solar Guide, 2018; Solar Southwest, 2017). To be in line with UKEV, only lithium-ion based systems were included. Four key characteristics of battery storage systems were identified as battery power, capacity, warranty as a measure of longevity and cost. Power is given as continuous output; capacity as nominal value; cost includes taxes, VAT, but excludes installation. Warranty is issued as DoD remaining after a given number of years or cycles. Table 5 shows the summary of the data collected from the manufacturers Tesla, Sonnen. Powervault, LG, BYD, Moixa and Samsung (BYD, 2017; LG, 2018; Moixa, 2018; Powervault, 2017; Samsung, 2018; Sonnen, 2018; Tesla, 2018).

Table 5

Overview of battery systems available for the UK market (BYD, 2017; LG, 2018; Moixa, 2018; Powervault, 2017; Samsung, 2018; Sonnen, 2018; Tesla, 2018).

Model	**Power (kW)**	**Capacity (kWh)**	**Warranty (DoD; years, cycles)**	**Cost (£)**
Tesla Powerwall 2	5	14	80%; 10, 6.5k[7]	5,900
sonnenBatterie	1.5-2.5	2-16 (2kWh steps)	70%; 10, 10k	4,500 (2kWh) +1,500/step
Powervault G200	0.8/1.6/1.6	2.2/4.4/6.6	50%; 10, 4k	3,000/4,200/ 5,400

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[7] Tesla does not limit the number of cycles of the Powerwall 2 for solar storage application. However, for non-solar storage applications the limit is 37.8 MWh of aggregate throughput measured at the AC output. This would be equivalent to 2,800 full discharges of the 13.5 kWh battery. Assuming a full charge/discharge cycle due to solar charging per day for ten years, this would mean total cycles equivalent to 6,450 (10 · 365 + 2,800 = 6,450).

LG Chem Resu	3.0/4.2/5.0	3.3/6.5/9.8	60%; 10, 2.5k	2,800/4,500/ 7,700
BYD B-Box Res	2.56/5.12/5.12/5.12	2.56/5.12/7.68/10.24	80%; 10, 3.6k	1,800/3,000/4,300/5,600
Moixa	0.43	2.0/3.0	80%; 5, 10k	3,000/3,800
Samsung SDI	2	3.6	80%; 5, 6k	3,500

Ikea's home battery system that is distributed in cooperation with Solarcentury is not included in this study, as the battery units are from LG Chem, which is already included in this analysis (IKEA, 2018). E.on's offering was also excluded from the analysis, as the modules offered once again are from LG Chem and Pylontech. The Mercedes-Benz home energy system was not included as the product has been discontinued (Spector, 2018).

To give an idea of the usable capacity, which is frequently quoted around 90% DoD (Schuller et al., 2014), and round-trip efficiency, typically around 90-95% (Byrne et al., 2017), the seven batteries were compared for those two characteristics. It was found that usable capacity ranged between 80% and 100%, with values frequently being at 90%. Sometimes the true nominal capacity of batteries is unknown, as OEMs do not always publish them. The exception being sonnenBatterie with 100% is probably due to the capacity being stated as usable, instead of nominal capacity. For round-trip efficiency, values ranged between 90 and 95%, but tended to be closer to the 95% mark. Table 6 summarizes the findings of usable capacity and round-trip efficiency for the seven battery systems.

Table 6

Further characteristics of the seven battery systems under consideration are useable capacity and round-trip efficiency to determine the real charge available and energy input required to achieve such charge.

Model	**Usable capacity (kWh)**	**Round-trip efficiency (%)**
Tesla Powerwall 2	13.5	90
sonnenBatterie	2-16 (2kWh steps)[8]	94
Powervault G200	2.0/4.0/6.0	95
LG Chem Resu	2.9/5.9/8.8 (90%DoD)	95
BYD B-Box Res	2.4/4.8/7.2/9.6	95
Moixa	1.6/2.4	n/a[9]
Samsung SDI	3.24	95

The previously used weighted methodology for UKEV could not be applied to UKBat due to the lack of sales data. Table 7 shows that the average battery was determined to have a continuous power output of 2.72kW, useable capacity of 6.23kWh and would cost £5,060 without installation costs

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[8] Assumed capacity is around 2.2kWh per module, but manufacturer states capacity and useable capacity as equivalents with 100% DoD.

[9] No round-trip efficiency could be determined for Moixa.

Table 7
Characteristics of the average UK home battery, called UKBat, calculated by taking the arithmetic mean of the selected battery systems.

Characteristic	**UKBat**
Power (kW)	2.72
Capacity (kWh)	6.63
Usable Capacity (kWh)	6.23
Round-trip efficiency (%)	94
Warranty (DoD; years, cycles)	71%; 8.6, 6.1k
Cost (£)	5,060

4.3 Battery costs and degradation

To determine the cost of using an EV battery as domestic storage, the value of the battery needs to be known as well as by how much each additional cycle or unit throughput affects its degradation.

4.3.1 Battery value

The price difference for the Renault Zoe sold without battery (with battery leasing) and with battery is £5,600 for a 40 kWh battery pack (Bingley, 2017). This would indicate a battery pack unit cost of 140 £/kWh. This seems rather low, as other sources state 159-190 £/kWh (209-250 $/kWh) of EV battery pack manufacturing costs in 2017 (BNEF, 2018c; UCS, 2018). However, Renault may be willing to sell the battery pack without a profit to keep prices as low as possible to gain initial market share of the emerging EV market. All sources agree on the general trend that the costs are decreasing and will continue to fall until 2030, after which predictions become difficult (Few et al., 2018). Overall, an average value for EV battery costs between real market prices and literature sources, gives a unit price of 165 £/kWh, which will be used for comparison purposes.

4.3.2 Battery degradation

A large-scale self-reported study of Tesla users showed less than 8% degradation for 1,000 cycles and 10% degradation for 250,000 km (Lambert, 2018; Matteo, 2018). These rates of degradation applied to the UKEV, assuming a use of battery up to 30% degradation, lead to degradation costs of 0.049 £/kWh. These values are slightly higher than the Peterson et al. assessment of degradation costs of 0.042 $/kWh for a PHEV battery pack costing $5,000 (Peterson et al., 2010). If the user would use the EV battery until 50% remaining DoD, then the degradation costs would drop further to 0.029 £/kWh. These values, which are based on real data, will act as the minimum boundaries of degradation estimations for the V2H scenarios analysed here.

Manufacturer warranties tend to guarantee around 160,000 km driving with a minimum remaining capacity of 70% for eight years (BMW, 2018; Nissan, 2018; Renault, 2017; Tesla, 2017). The UKEV uses 0.1786 kWh/km, thus under warranty total throughput would be 28,572 kWh with a cost of 0.23 £/kWh, as guaranteed under the warranty. If the user would use the EV battery until 50% remaining DoD, then the degradation costs would go down to 0.14 £/kWh. This can be assumed to be the maximum of any degradation costs.

Thus, to make this study more robust, three energy-related degradation rates lying between the minimum and maximum will be used. The lowest values ranged between 0.029-0.049 £/kWh, based on real driving data (Lambert, 2018; Matteo, 2018). Table 8 summarises the energy-based battery degradation rates that will be used for the UKEV. The highest value will be taken from within the warranty range of 0.14-0.23 £/kWh, and a medium value will be taken in between the real-driving and warranty value. The values used will be rounded to 0.04 £/kWh, 0.08 £/kWh and 0.16 £/kWh. This corresponds well to Schuller et al.'s degradation values who used 0.05 €/kWh, 0.1 €/kWh and 0.2 €/kWh in 2014[10] (Schuller et al., 2014).

Table 8
Summary of range of degradation levels to be used for UKEV

Degradation level	Final value (£/kWh)	Range (£/kWh)	Based on
Low	0.04	0.029-0.049	Real driving data
Medium	0.08		Between low and high
High	0.16	0.14-0.23	Warranty guarantee

Bashash et al. determined that high-rate charging will lead to faster battery degradation, especially at low and high SOCs, and found the correlation to be quadratic (Bashash et al., 2011). Therefore, the charging rate must be considered and following Bashash et al., Schuller et al. modelled it as a quadratic term 0.01 £/kWh^2, which will be used for this paper (Schuller et al., 2014).

In addition to battery degradation, charging efficiency of the battery and discharging efficiency of the power electronics and inverter must be considered. These can both be taken as 93% (Schuller et al., 2014; Tomić and Kempton, 2007).

5. Results

This section outlines the results of using the UKEV and UKBat in a V2H scenario as a domestic battery to shift consumption from peak to off-peak using tariff price differences. Domestic battery systems on the market are currently designed to store consumers' own renewable energy generation, mostly PV. In addition, if there is a proper tariff design, they can also be used for load shifting purposes and storing electricity when it is cheap. In this study, PV use is neglected. The batteries are only used for shifting consumption by using time-of-use tariffs, which should not impact battery performance negatively as usage is similar to that of renewable energy shifting.

5.1 UKEV

For the EV calculations as domestic storage system, it will be assumed that the EV and bi-directional charging equipment are already in place. Therefore, these costs will not be part of the calculation, as the potential use of gains from V2G functionality would also need to be considered, which under the current methodology they are not. The costs will be calculated as the additional degradation to the battery resulting from V2H usage.

5.1.1 EV Consumer Behaviour

EV charging requirements depend on the number of vehicles, user type and day of the week. The Low Carbon London Learning Lab study on EV deployment has been the most comprehensive UK EV study

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[10] 0.05€ converted to GBP using 2014 conversion rates and then adjusted for inflation gives 0.04£.

to date (Aunedi et al., 2014). The findings of driving behaviour are in line with previous studies that determined the average journey length in the UK as below 11 km and 93% of round-trip journeys below 120 km (Jamasb and Pollitt, 2011, p. 221). The shorter distances found by Aunedi et al. are likely due to the urban nature of the study. Table 9 presents answers to the questions of where, how long, how much and when charging occurs. Another study on residential EV users determined that the SoC, when connected for the first charging event, was between 25% and 75% for more than 70% of EVs (Quirós-Tortós et al., 2015). As most people want to plug-in their EVs as soon as they arrive at home, a smart charging system is required to avoid charging but instead use the EV battery as a power source.

Table 9

Residential user EV charging behaviour (Aunedi et al., 2014)

Characteristic	**Value**
Home charging	84%
Public charging points	16%
Charging duration	2 hrs, very few more than 5 hrs
Median trip distance	3.5 km
95% of trips less than	25 km
Daily energy demand	3.57 kWh (17.5 km urban)
Highest demand time for charging	18:00 to 0:00

There is a sharp decrease in stationary EVs from 7:00, and a steep increase from 18:00 (Aunedi et al., 2014). Therefore, during an average weekday the EV will be treated as at home from 18:00 to 7:00. This would change for the weekend, as people start their days later as businesses are shut. It will be assumed that for the weekend, the EV is home from 17:00 to 22:00.

5.1.2 Two-rate and three-rate tariffs

For simplification purposes, the Economy 7 hours will be assumed to be from 0:00 to 7:00 for the two-part tariff. This will be used in combination with the average off-peak tariff at 0.079 £/kWh and day rate at 0.174 £/kWh (BEIS, 2018). For the three-rate tariff, the Green Energy UK tide tariff will be adopted and used, with the peak pricing only in place during the week from 16:00 to 20:00 (BEIS, 2018).

In both tariff scenarios, the EV is ideally used as supply for the home between 18:00 to 0:00 during the week, and 17:00 to midnight and 7:00 to 10:00 during the weekend, and always charged during the lowest tariff from 0:00 to 7:00. This means that the SoC will be sufficient for leaving as charging occurs overnight prior to departure. The three-hour discharge on weekend mornings will only require a few kWh, meaning the battery will remain sufficiently charged. Figure 1 depicts how the two tariffs compare against EV driving behaviour.

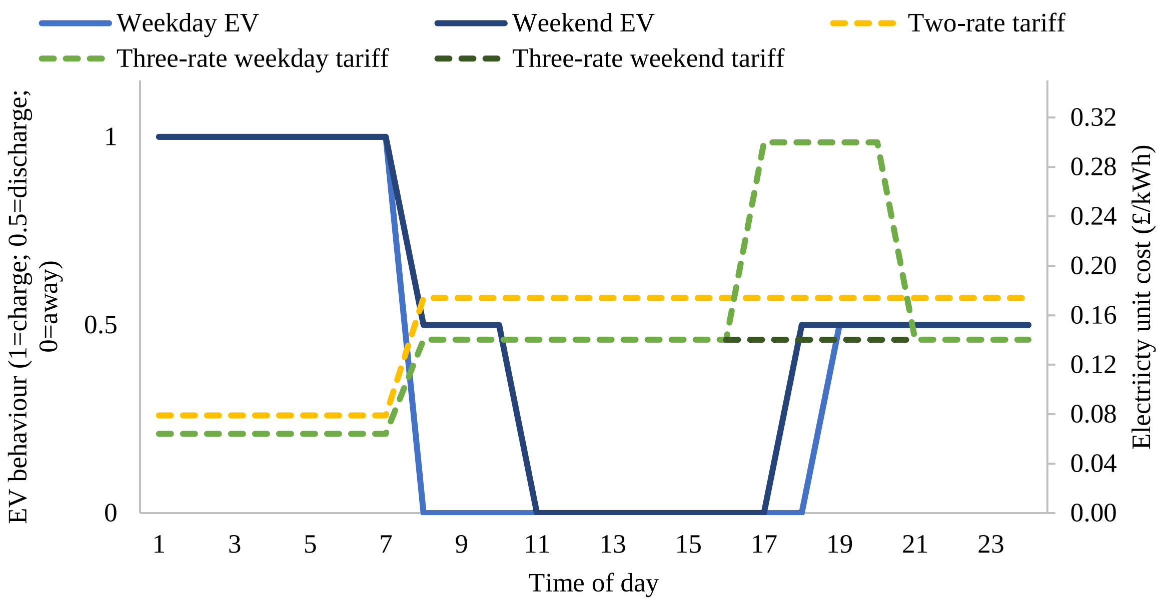

Figure 1. EV behaviour during week and weekend against two-rate and three-rate tariffs

5.1.3 EV Results

Four sets of results are presented in this section. The first set of net and percentage savings are compared to how much consumers would pay on the two-rate and three-rate tariffs, with the same consumption behaviour. The second set of net and percentage savings are adjusted to what consumers would have paid on their existing flat or two-rate tariff. For both tariffs, the consumption values were adjusted from statistical data on weekdays and weekend behaviour. Table 10 summarises the consumption that can be shifted under the two tariff structures. Table 11 shows annual bills for the two profile classes with no behavioural change.

Table 10

Yearly consumption (kWh) that can be shifted for UKEV, calculated as percentages from PCs (UKERC, 1997), and adjusted to medium TDCVs (Ofgem, 2017a)

	Two-rate tariff		**Three-rate tariff**	
	Profile Class 1	Profile Class 2	Profile Class 1	Profile Class 2
ΔE week	850	750	n/a	n/a
ΔE weekend	463	462	n/a	n/a
ΔE_1 week	n/a	n/a	297	261
ΔE_2 week	n/a	n/a	554	489
ΔE_2 weekend	n/a	n/a	463	462
ΔE	1,314	1,212	1,314	1,212

Table 11

Summary of annual electricity bills (£) for customer groups under all tariffs

Tariff	**PC1**	**PC2**
One-rate	446	n/a[11]
Two-rate	495	563

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[11] There are no PC2 customers on the flat one-rate tariff.

Three-rate	485	521

Table 12 summarises the savings for consumers when switching from. PC1 is seen as switching from the one-rate tariff to the two-rate and to the three-rate tariff and PC2 switches only from the two-rate tariff to the three-rate tariff. For PC1, the savings range from losing £121 to saving £96 when switching to the two-rate tariff. These figures are higher for PC1 when switching to the three-rate tariff, with maximum losses of £85 and savings up to £132. The PC1 two-rate tariff no longer yields a net saving under the medium rate degradation scenario. For PC2 under the two-rate tariff, savings range from losing £66 to gaining £133. An increase can be observed in savings under the three-rate tariff for PC2, where customers switch from two-rate to three-rate.

Table 12

Net savings (£) and percentages of annual average electricity bill for customers who would switch from one-rate or two-rate tariffs if they use UKEV for 1 year, where negative values indicate a loss.

	One-rate (PC1) or two-rate (PC2) to two-rate tariff		**One-rate (PC1) or two-rate (PC2) to three-rate tariff**	
Degradation	Profile Class 1	Profile Class 2	Profile Class 1	Profile Class 2
0; 0	96 (22%)	133 (24%)	132 (30%)	197 (35%)
0.04; 0.01	37 (8%)	79 (14%)	73 (16%)	142 (25%)
0.08; 0.01	-16 (-4%)	31 (5%)	20 (5%)	94 (17%)
0.16; 0.01	-121 (-27%)	-66 (-12%)	-85 (-19%)	-3 (-1%)

5.2 UKBat

The calculation for the UKBat system savings will be very similar to that of the UKEV. System costs will not be factored in the calculations as these will be accounted for through the cost of battery degradation. The assumption will be made that the battery can provide peak demand of the household at any time with 2.72 kW, where the household demand does not exceed 2.5 kW.

5.2.1 Battery degradation differences

The UKBat battery degradation costs will be slightly different than those from the EV’s. By splitting the established cost of the UKBat and inverter over its capacity, the following replacement cost would be obtained:

$$Replacement\ cost = \frac{£5{,}060}{6.63kWh} = 763\ £/kWh$$

This includes the inverter and other power electronics, and the unit comprising the battery cells. From Table , the average warranty determined for the UKBat was 6,100 full cycles or 8.6 years with a remaining depth of discharge of 71%. At a usable capacity of 6.23 kWh and using system costs of £5,060, the warranty guaranteed degradation costs would be:

$$Warranty\ degradation\ cost\ (DoD\ 71\%) = \frac{£5{,}060}{6{,}100\ cycles\ \times\ 6.23\ kWh} = 0.133\ £/kWh$$

If the battery lifetime is assumed to be longer than the warranty and used until 50% remaining DoD as done with the EV, degradation costs drop. The battery could be used far longer than to a DoD of 71%

as it is stationary, and efficiency is not that important. First finding the right number of cycles for degradation up to 50%, and then re-calculation the new degradation cost:

$$Cycles\ at\ DoD\ 50\% = 6{,}100\ cycles \times \frac{50}{29} = 10{,}517\ cycles$$

$$Warranty\ degradation\ cost\ (DoD\ 50\%) = \frac{£5{,}060}{10{,}517\ cycles\ \times\ 6.23\ kWh} = 0.077\ £/kWh$$

The EV lithium-ion battery unit price used was 165 £/kWh. Using this value as the replacement cost for UKBat shows the low-end degradation costs possible as battery prices continue to fall:

$$Low\ degradation\ cost\ (DoD\ 71\%) = \frac{165\ £/kWh\ \times 6.63kWh}{6{,}100\ cycles\ \times\ 6.23\ kWh} = 0.029\ £/kWh$$

$$Low\ degradation\ cost\ (DoD\ 50\%) = \frac{165\ £/kWh\ \times 6.63kWh}{10{,}517\ cycles\ \times\ 6.23\ kWh} = 0.017\ £/kWh$$

Table 13 summarises the energy-based battery degradation rates that will be used for the UKBat system.

Table 13

Summary of range of degradation levels to be used for UKBat

Degradation level	Final value (£/kWh)	Range (£/kWh)	Based on
Low	0.03	0.017-0.029	Low battery prices
Medium	0.06	n/a	Between low and high
High	0.12	0.077-0.133	Warranty guarantee

Similarly, to the UKEV degradation values, three values covering this range of degradation rates will be used. One for low, medium and high degradation rates. These will be at 0.03, 0.06 and 0.12 £/kWh, respectively. These are lower than the values used for EV battery degradation rates, which is mostly due to being able to use the battery to a lower remaining DoD as the battery is stationary. Furthermore, the nature of the system means that it is designed for more cycles at continuous output rather than the EV battery, designed for a range of power outputs, and less constant demand.

5.2.2 Battery usage

In terms of usage, the issue of being at home does not exist for the domestic battery as it is a permanent installation. Therefore, the only limiting factor of a daily use cycle is the usable capacity, which for the UKBat was identified as 6.23 kWh with a round-trip efficiency of 94%. The two tariffs used will be the same as outlined previously, a two-rate and a three-rate tariff and applied to PC1 and PC2. For the three-rate tariff, priority will be given to switching all use away from the most expensive time from 16:00 to 20:00. All remaining battery capacity will be used for shifting consumption from the rest of the day.

5.2.3 Battery Results

The methodology used to determine the consumption during certain times of the day and week is the same as the one used for the UKEV. The only difference is that the total amount that can be shifted is limited by the usable capacity of the battery in some cases, which is indicated through the use of brackets for the maximum potential that could have been shifted. Table 14 shows the consumption values that can be shifted for UKBat. For the three-rate tariff, ΔE_1 presents the shift from peak to off-peak tariff and ΔE_2 the shift from the standard day tariff (medium tariff) to the off-peak tariff.

Table 14

Yearly consumption (kWh) that can be shifted for UKBat, calculated as percentages from PCs (UKERC, 1997), and adjusted to medium TDCVs (Ofgem, 2017a)

	Two-rate tariff		**Three-rate tariff**	
	Profile Class 1	Profile Class 2	Profile Class 1	Profile Class 2
ΔE week	1,620 (1,873)	1,620 (1,665)	n/a	n/a
ΔE weekend	648 (755)	648 (692)	n/a	n/a
ΔE_1 week	n/a	n/a	538	456
ΔE_2 week	n/a	n/a	1,082 (1,335)	1,164 (1,209)
ΔE_2 weekend	n/a	n/a	648 (755)	648 (692)
ΔE	2,268 (2,628)	2,268 (2,357)	2,268 (2,628)	2,268 (2,357)

Similar to UKEV, the savings adjusted to what customers paid with the existing tariffs show the net savings possible with the UKBat system. Table 15 presents the net savings for customers who would switch from their current tariffs to the two-rate and three-rate tariffs. As for UKEV, PC1 switching to two-rate yields the worst results, with maximum savings of £181 and losses up to £111. For PC2 savings go up to £229 under the two-rate tariff and increase under the three-rate tariff. For the "no degradation" scenario, PC2 customers shifting to a three-rate tariff can save around £303 annually compared to current bills. This represents 54% of annual electricity bills. Low and medium degradation scenarios yield a range of 6% (for PC1) to 38% (for PC2) of savings when compared to annual electricity bills under the existing tariff structures.

Table 15

Net savings (£) and percentages of annual average electricity bill for customers who would switch from one-rate or two-rate tariffs if they use UKBat for 1 year, where negative values indicate a loss.

	One-rate (PC1) or two-rate (PC2) to two-rate tariff		**One-rate (PC1) or two-rate (PC2) to three-rate tariff**	
Degradation	Profile Class 1	Profile Class 2	Profile Class 1	Profile Class 2
0; 0	181 (41%)	229 (41%)	237 (53%)	303 (54%)
0.03; 0.01	93 (21%)	141 (25%)	149 (33%)	215 (38%)
0.06; 0.01	25 (6%)	73 (13%)	81 (18%)	147 (26%)
0.12; 0.01	-111 (25%)	-63 (-11%)	-55 (-12%)	11 (2%)

6. Discussion

This chapter discusses the results for UKBat and UKEV, investigating the differences between type of consumer, tariff structure and battery degradation rates. We can list several main points about the discussion;

- Proper tariff design is a must in achieving larger savings.
- Battery degradation data are crucial in calculating the net savings through load shifting.
- If PC1 customers switch from the flat-tariff to the three-rate tariff, under low battery degradation scenario, UKBat owners will make a saving of £149 annually (33% of the annual

electricity bill), whilst UKEV owners will save £73 per year (16% of the annual electricity bill). The difference between savings might not big enough to motivate the customers to buy extra batteries for their homes if they already own an EV since savings through load shifting will be a supplementary benefit to the EV owners in addition to its main purpose, which is mobility and transport.

- The increasing rooftop solar photovoltaic (PV) use will change this behaviour since PV generation will take place during day times when the EV will likely to be away from home. The case will shift from load shifting in the peak times to storing energy during day time and using this or selling it back to the grid in the peak time. The PV and battery use cost assessment is a different topic that needs further and extensive analysis. Therefore, it is left out of the scope of this paper intentionally.
- Demand Response, load shifting measures and increasing uptake of domestic battery and V2H adoption might lead lower price differentials in the tariffs due to flattened load profiles. This will naturally decrease the total amount of savings that the customers can make by using domestic storages.
- EVs will likely undermine the market for batteries and that exploiting time of use tariffs could be a good additional source of value for an EV. We should stress that V2H will be a secondary benefit of owning an EV, however the user will pay for the domestic battery just for the saving purposes, which will be its main function. Table 16 in the Conclusion section summarises the expected total benefits of V2H.
- One of the main disadvantages of extra domestic battery use will be the spacing problem. For example, the dimensions of Tesla PowerWall are 115 cm x 75.5 cm x 15.5 cm (45.3 in x 29.7 in x 6.1 in) (Tesla, 2018). Fitting this equipment in small-sized apartments might be a deterring idea for the residential users. A solution to this might be providing shared battery installations for all residents in the new apartment blocks.
- Rate of return of the investment analysis is neglected intentionally. The primary function of the EV will be mobility and transportation, whereas V2H will be a secondary benefit for the EV owners. Similarly, the residential customers will likely to own batteries together with their rooftop PV panels. By that way, the primary objective will be storing the solar energy produced during day time, when the customer will be away from home. Since solar rooftop PV generation and load balancing is omitted in this paper, let us assume that the UKBat is used only for peak-demand shifting. Then, under medium battery degradation scenario, the annual saving for a PC1 customer shifting from flat-rate tariff to three-rate tariff will be £81. The cost of UKBat is around £5,060. This means the investment will be returned only after 62.5 years of time.

The comparison by Profile Class shown in Figure 2 and Figure 3 shows that PC1 consumers can achieve more savings than PC2, despite consuming less electricity in total. This is due to PC2 customers already being on a two-rate tariff and having shifted significant levels of consumption into the cheaper off-peak period. On average, PC1 customers save 7% more than their PC2 counterparts for the low and medium degradation rates. Broken down by tariff type, this gives 3% more savings for two-rate and 10% more for three-rate tariffs. However, the UKBat savings were limited by its battery capacity under both tariff structures.

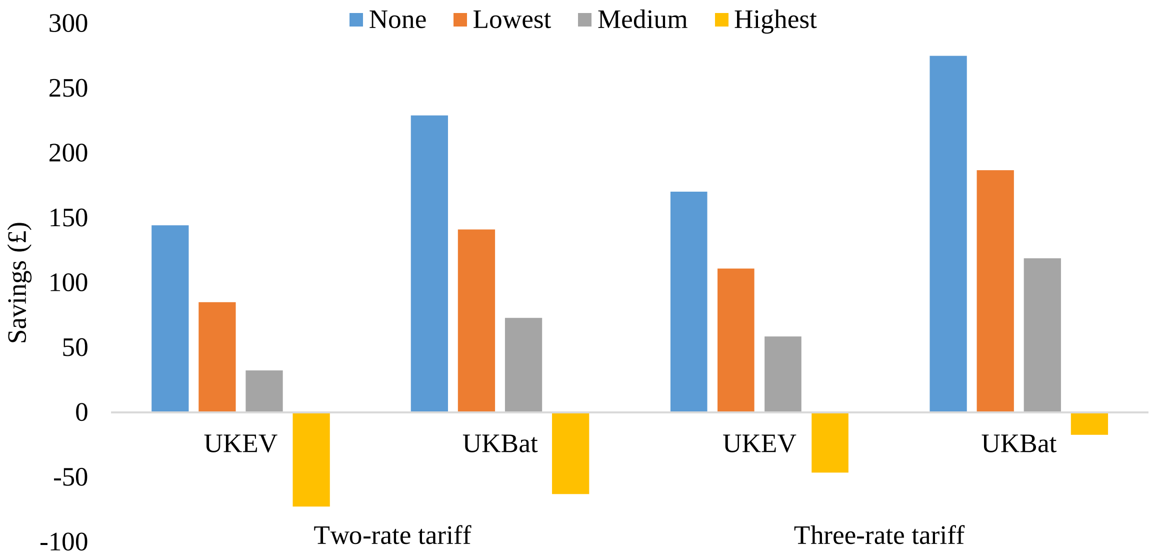

Figure 2. Annual saving comparisons for PC1 (regular domestic customers consuming 3,100kWh annually) with UKEV and UKBat under None, Lowest, Medium and Highest degradation scenarios.

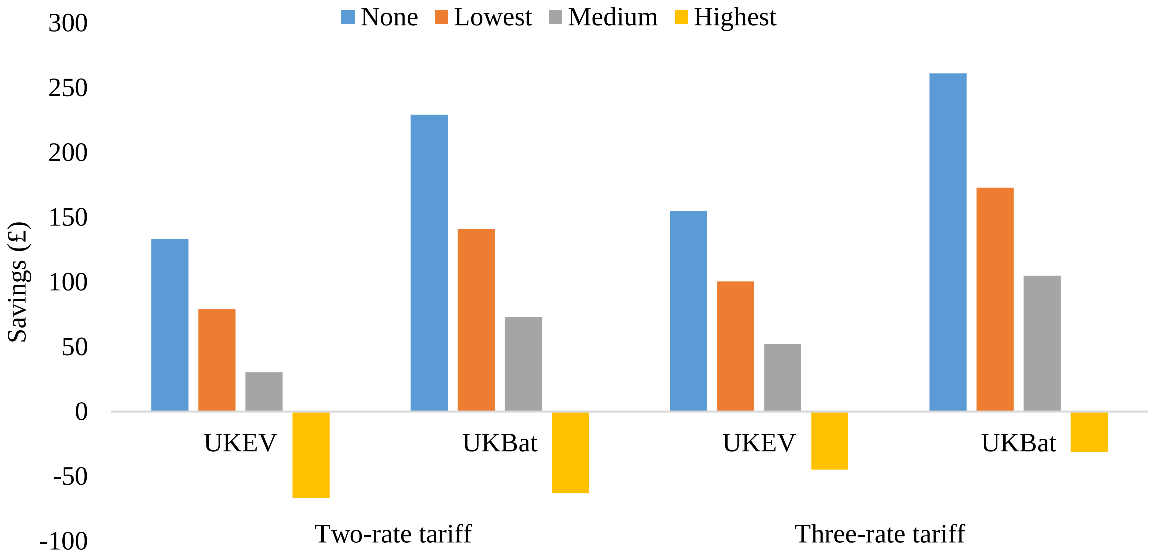

Figure 3. Annual saving comparisons for PC2 (Economy 7 customers consuming 4,200kWh annually) with UKEV and UKBat, under None, Lowest, Medium and Highest degradation scenarios.

Trends also shows that the three-rate tariff has larger savings than the two-rate tariff. This is expected as the price differential between peak and off-peak hours for the three-rate tariff is much larger than for the two-rate. Results also show that for the low and medium battery degradation rates, there is 30% extra saving on the three-rate over the two-rate tariff. For different customer classes, this means 33% more savings on average for PC1 and 28% higher savings for PC2.

7. Conclusion

Most studies have analysed the prospects and opportunities of V2G as this could bring about systemic change to the electricity grid by providing large-scale load balancing opportunities. However, they have mostly failed to consider the consumer's point of view and the need for economic or other incentives to encourage consumer participation in such schemes. V2H presents an easier starting point for motivating the consumers as it does not require collaboration of DNOs, suppliers and the national grid. The literature has shown gaps in the research of using EVs in the context of V2H from the customers' perspective, which was the focus of this UK-based study.

An average EV and domestic battery system were determined for the UK. Sales or registration data could not be determined for home batteries, and thus the methodology had to be slightly adjusted to include models based on popularity determined from installer guides. However, realistic features were found for both the UKEV and UKBat. Table 16 summarises the comparison of the main features of UKEV and UKBat.

Table 16
Main features of UKEV and UKBat

Trial / product	Concept and value proposition	Power (kW)	Capacity (kWh)	Cost (£)	Annual savings from switching to a three-rate tariff (£)[12]
UKEV	Mobility and transport, reduced CO2 emissions, peak demand reduction, improved grid stability	130	35.9	35,986	PC1: 20 PC2: 94
UKBat	Energy storage, peak demand reduction, improved grid stability	2.72	6.23	5,060	PC1: 81 PC2: 147

The findings indicate that both an EV and a domestic battery are likely to create some savings for the households when used for shifting consumption from peak to off-peak periods with time-of-use tariffs. Around 90% of UK consumers would fall under PC1. If PC1 customers switch to a three-rate tariff, then the UKEV annual savings will range from £20 to £73 (5% to 16% on annual electricity bills) for the medium and low battery degradation scenarios respectively. For UKBat, these ranged from £81 to £149 (18% to 33% on annual electricity bills) again for the medium and low degradation scenarios respectively.

The parameter that affects the savings the most is the rate of battery degradation and its associated costs. The price differential between peak and off-peak rates is also significant on total savings. Electricity prices are also an important parameter, as variations in these can greatly affect net savings.

Although the battery degradation costs are the largest factor at the time of this study, this may change in the future, as battery cell costs are predicted to continue to fall (BNEF, 2018c; Field, 2016). Additionally, electricity prices are expected to continue to rise (UKPower, 2018). Even with the relative

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[12] Taken at medium battery degradation rate.

saving remaining the same, it might bring about greater net savings, which are more likely to gain consumers' attention.

The approximations used for calculating the battery degradation rates are limited as they rely on academic models developed in laboratory environments This study makes use of battery degradation data from various academic and grey literature sources (Ashwin et al., 2018; Bashash et al., 2011; Schuller et al., 2014; Uddin et al., 2017b).

It can be concluded that it is not wise or profitable to use both a domestic battery system and V2H at the same time. A decision between a domestic battery or using an EV with V2H has to be made. An EV owner may naturally favour V2H as he already has the battery in his car and does not have to purchase a new one in the form of a domestic battery. However, if a domestic renewable installation is present such as a rooftop PV panel, then this outlook may change as more electricity can be stored throughout the day during which the EV is not available at home. A consumer who owns neither and is looking to save on electricity bills may favour the domestic battery system as the lower investment makes it more attractive. Nonetheless, it must be noted that within the context of this study, V2H used has always been considered as a secondary benefit to owning an EV rather than its primary function.

Additional research into the battery degradation caused by V2H and other V2G services is required, especially with a focus on collection of real life data as it seems unlikely that manufacturers are going to release their data of battery degradation rates due to protecting commercial interests. Investigating smart charging and optimised cycles seems promising too, as this potentially could eliminate the negative effects of V2G functionality as Uddin et al. have shown, which could potentially eliminate the warranty barrier (Uddin et al., 2017b).

Furthermore, energy utilities must offer consumers more options for time-of-use tariffs. Currently, only one three-rate tariff was identified as available to domestic clients in the UK: The number of these must increase to encourage uptake of V2H technology and allow for greater demand side management. Tariff structures designed specifically for EV users may also be worth considering as more EVs penetrate the market. Governments could also accelerate this process by incentivising consumers to use less electricity during peak hours by coupling the plug-in grant incentive with time-of-use and even specific V2H or V2G tariffs.

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