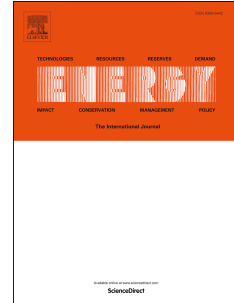


# Journal Pre-proof

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**Yazan Al-Wreikat:** Methodology, formal analysis, writing – original draft

**Emily Kate Attfield:** Investigation, writing – original draft

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Journal Pre-proof

## **Model for Payback Time of Using Retired Electric Vehicle Batteries in Residential Energy Storage Systems**

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## Abstract

This work presents a mathematical model for the payback time of reusing electric vehicle batteries as residential energy storage systems from the end of life of automotive application. The model was developed using MATLAB software and calculates the payback time of a battery energy storage system (BESS) under different scenarios while considering the daily electricity consumption profile for a UK household. The results show that battery purchase price, BESS capacity, electricity unit rates and electricity demand profile are variables with large effects on the payback time. At the simulated baseline condition with residential households of two people, a BESS using second-life batteries from five different vehicle models showed payback time ranging from 8.3 to 12.8 years. The combination of battery rightsizing to attend peak and standard demand, battery price drop by 46%, reaching the level where EV price becomes competitive with conventional vehicles, and BESS application to three or more households provides the most favourable scenario with the minimum payback time of 4.8 years. Further reduction in the payback time of up to 41% can be achieved with subsidised off-peak electricity unit rate.

**Keywords:** Electric vehicle batteries, battery energy storage system, payback time, reusability study, energy model.

## 1 Introduction

The reuse of batteries after end-of-life for automotive application experiences an increasing demand as batteries are discarded from electric vehicle (EV) utilisation with below 80% of primary capacity remaining [1]. These batteries can still perform in an energy-storage mode for more than additional 10 years, reducing the battery waste produced [2] and extending their useful life in applications of less power intensity instead of sending them to landfills [3]. The reuse of discarded EV batteries as energy storage systems (ESS) provides massive environmental benefits, and may bring economic advantages. Repurposing used EV batteries may also help EV owners to recover some of the initial vehicle cost [4]. With a race to find sustainable recycling methods and avoid irreversible climate change, the lifetime extension of used EV batteries by reusing them as ESS promptly contributes to reduce environmental impacts. Overcoming economic and technical obstacles is required to implement the use of second-life batteries and progress recycling rates [5].

Lead-acid batteries are the most commonly used in ESS due to their low investment costs resulted from 150 years of consolidated technology [6], but suffer from low energy density, short life and heavy weight [7]. In comparison, lithium-ion batteries show advantages over lead-acid batteries such as high energy and power density, low maintenance and high number of cycles [8]. Furthermore, the costs of lithium-ion batteries are reducing at a rate of 8-16% per annum, thus removing the biggest barrier for their use in ESS [9].

A review of the Tesla Powerwall ESS reveals the cost of the new technology starting at US\$ 8000 and specification of 13.5 kWh capacity [10]. This ESS can be a highly competitive option to reuse EV batteries due to its many benefits, such as capacity and increased expected lifetime. By 2025, roughly 75% of spent EV batteries will be reused in second-life applications after returning from vehicles and then recycled to recover all the valued components [11].

The economics of reusing batteries depends on many factors, according to their utilisation in the commercial, industrial or residential sector. The variables that can affect the economic feasibility of reusing batteries are the initial cost of batteries [12], integration with solar [13] or wind power [14], ageing performance [15], remaining capacity [16] and electricity price and demand [17]. The initial cost of batteries is the most important factor, as repurposing batteries can distribute the initial cost to other users [12]. Integration with solar or wind power can bring economic benefit with large-scale installation if their energy prices decrease rapidly [13, 14]. Ageing performance and remaining capacity determine the value and service lifetime of second-life batteries [15, 16]. Electricity price and demand dictates the saving based on the difference between peak and off-peak rates [17].

In most cases, the reuse of EV batteries is deemed more economical in the industrial sector due to more attractive electricity tariffs [17]. Several major car manufacturers showed interest in second-life batteries through involvement in large scale research projects to test and validate their commercial use [18] and search for an alternative revenue stream [19]. Also, a start-up EV company designed their vehicle battery pack to easily transform it into a stationary ESS at the end of vehicle life [20]. The shortest payback time of 1.5 years was found for a battery energy storage system (BESS) based on multiple second-life batteries from EVs integrated to a smart grid system to be used as a backup energy source for a generation unit [21]. However, it is recognised that BESS do not bring economic benefits when integrated with solar photovoltaics systems in European countries according to a recent study [22].

The three most important economic factors for the use of BESS are electricity tariffs, government incentive policies, and the cost of repurposed electric batteries. The initial price is the most crucial factor for the economic performance of reused batteries in ESS for the residential sector, which lags behind commercial and industry sectors as subsidy is still needed to make a profit in China [23]. An economic study of reusing batteries in energy storage of fast

charging systems for EVs in five US cities under different configurations showed the payback time was less than the project lifetime of 10 years in all locations except for one due to flat electricity price [24]. Further research is needed on the economic benefits of repurposed batteries for small scale consumers as current market prices make these batteries cheaper and more accessible compared to new ones [25]. ESS are mainly used in residential applications to perform peak shaving or energy arbitrage [26]. Compared to a peak shaving strategy, energy arbitrage is more economically feasible as it generates higher savings and could indirectly make peak shaving [27]. The domestic sector largely contributes to peak electricity demand in the UK during winter [28], thus providing additional backing to incentivise the installation of used batteries as ESS in residential building.

In summary, the literature shows that the possibility of reusing EV batteries as ESS depends on a case-to-case analysis, with different variables affecting the payback time in diverse ways. Electricity tariffs are one of the most significant variables that affect the payback time, with systems like TOU (time of use) residential rate plan playing a major role as an incentive strategy. Combining a TOU tariff with a household battery could generate savings through load shifting away from the high price period [29]. With the price of EV batteries decreasing and electricity tariffs on the rise, the use of retired battery in ESS can soon become economically feasible. There are a few studies analysing the benefits of using BESS in the industrial sector, however, published research on the economic benefits of the use of BESS in the residential sector is very limited. Thus, the objective of this work is to address this research gap by developing a mathematical model for calculation of the payback time of adopting BESS using retired, second-life EV batteries for residential users. The main novelty of this work is the identification and use of key parameters and the build-up of realistic scenarios that allowed the model to point out the conditions of BESS utilisation with minimum payback time.

Next, the paper is structured in three main sections. Section 2 describes the methodology applied to create the model and the source of data. Section 3 presents the results and discussion based on the outcomes from the model. Finally, section 4 concludes the paper with a summary of the main findings.

## 2 Methodology

The BESS considered in this study works on the principle of energy arbitrage, where electricity is stored during low prices and afterwards discharged when the prices are higher [30]. The main parameters considered in the model calculations are battery price, energy capacity, daily electricity consumption, BESS parameters, electricity unit rates and daily periods when special rates are applied. The initial model assumptions include the battery state of health (SOH), the actual used battery capacity of energy storage relative to its original capacity, as an indicator used to ensure reliable and safe operation of the battery [31]. The absolute SOH of an end of life battery in automotive mode is generally set at 80% [32]. If battery performance degrades to a certain level, battery leakage, insulation damage, and partial short circuit issues can lead to disastrous accidents [33]. Repurposed batteries from the automotive sector are projected to last for an additional 10 years in ESS applications [34]. In order to avoid any catastrophic incidences caused by dramatic changes in ageing and battery degradation behaviour, a 60% SOH has been considered as the limit the BESS can reach during second use [35].

The second-life battery of a BESS can degrade at a rate of 1% to 3% per year [25]. Based on 10 years projected life and value of 60% SOH at the end of life, the degradation rate ( $\alpha_{deg}$ ) used in this study was calculated to be 2.8% per year. Setting certain limits on an used battery state of charge (SOC) during operation can minimise cycle ageing and extend battery



life [36]. The second-life battery of a BESS discharges during a given cycle between 80% and 20% SOC, corresponding to 60% depth of discharge (DOD), a typical value used in the literature [25]. Therefore, the usable battery capacity  $E_{usable}$ , in kWh, can be calculated as follow:

$$E_{usable} = E_{bat} \cdot SOH_i \cdot \beta_{DOD} \cdot \eta_{dis} \cdot (1 - \alpha_{deg})^k \quad (1)$$

where  $E_{bat}$  is the new battery capacity, in kWh;  $SOH_i$  is initial state of health set at 80% of the new battery capacity [32];  $\beta_{DOD}$  is the used battery DOD;  $k$  is the second-life battery operation time in the BESS, in years; and  $\eta_{dis}$  is the discharging efficiency when the battery provides electricity to the house, assumed as 90% [34].

The battery parameters, included the purchase price, were based on the Mitsubishi Outlander, one of the most common plug-in hybrid electric vehicle (PHEV) models sold in the UK [37]. This vehicle battery was chosen because its energy capacity of 13.8 kWh [38] is adequate to attend the average annual electricity consumption of residences, reported to be around 4200 kWh for medium type users [39]. The cost of the Mitsubishi Outlander new battery was calculated based on the current battery price of £180/kWh at a pack level [40]. An additional 20% was added as VAT, making the baseline price for a new battery 216 £/kWh. The cost of a repurposed battery is considered 20% of a new battery [17].

Table 1 shows the model baseline input data for the simulation. Some of the data sources in this study related to costs use different currencies to the UK. A fixed exchange rate is used to convert the prices to pound sterling based on the average exchange rate for the year 2020 [41]. The total cost of the residential BESS with second-life battery,  $C_{BESS}$  (£), is calculated as follows:

$$C_{BESS} = (C_{bat} + C_{bms}) \cdot (1 + \beta_{inst}) \quad (2)$$

where  $C_{bat}$  is the used battery purchase cost (£) and  $C_{bms}$  is the price of the battery management system (BMS), here is considered at a fixed value of £1329. The BMS is also used to prolong the batteries life by ensuring a safe and reliable operation [42].  $\beta_{inst}$  is an added 5% to the total BESS price as installation cost [2].

The varying electricity unit rates are according to the rising amount of TOU tariffs offered by electricity providers, where the customers are encouraged to shift their electricity usage from peak to off-peak times and can bring several economic, reliability and environmental benefits [43]. Several electricity providers introduced energy tariffs with reduced unit costs during off-peak times, made for EV owners to promote charging their vehicles during lower electricity demand [44]. Using the same incentive to charge BESS, the time split and unit rates for peak, standard and off-peak electricity consumption considered by the model are obtained from Küfeoğlu [45] based on data available from a major electricity provider. Table 2 details the rates and periods for the three-rate tariff used for this model. The main model output is the BESS payback time, considering the normal daily operating costs and the savings when the BESS is used.

The electricity consumption for residential household used in the model was obtained from the Household Electricity Survey (HES), which monitored the electricity consumption of 250 homes in the UK [46]. Figure 1 shows the electricity consumption profile for a typical household in the UK using HES data and the time each electricity rate is applied. From the household profile curve and consumption occurring during peak period  $E_{pk}$ , standard period  $E_{std}$  and off-peak  $E_{opk}$ , in kWh, one can obtain the total daily electricity consumption  $E_{day}$ , in kWh. Therefore, the normal daily cost of electricity consumption without BESS,  $C_{day}$ , is calculated as:

$$C_{day} = E_{pk} \cdot c_{pk} + E_{std} \cdot c_{std} + E_{opk} \cdot c_{opk} \quad (3)$$

where  $c_{pk}$ ,  $c_{std}$  and  $c_{opk}$  are the peak, standard and off-peak electricity unit rates, respectively, in £/kWh.

The model considers that, for operation with BESS, the battery is only charged in the off-peak period. Initially, it is assumed that the battery is daily charged to the same amount of energy consumed from the BESS during the peak and standard periods. Thus, the daily cost of electricity consumption with activated BESS,  $C_{day,BESS}$ , is given by:

$$C_{day,BESS} = \left( \left( \frac{E_{pk} + E_{std}}{\eta_{ch} \cdot \eta_{dis}} \right) + E_{opk} \right) c_{opk} \quad (4)$$

where  $\eta_{ch}$  is the charging efficiency when the battery charges from the grid, equals 90% [34], similar to discharging efficiency.

Equation (4) is only applicable if the usable battery energy capacity is higher than the sum of the electricity consumed during peak and standard periods. If the usable battery energy capacity is equal to or lower than the combined peak and standard period consumption but higher than the peak period daily electricity demand, then:

$$C_{day,BESS} = (E_{pk} + E_{std} - E_{usable})c_{std} + \left( \left( \frac{E_{usable}}{\eta_{ch} \cdot \eta_{dis}} \right) + E_{opk} \right) c_{opk} \quad (5)$$

If the usable battery energy capacity is equal to or lower than the peak period daily electricity consumption, then the daily cost is calculated by:

$$C_{day,BESS} = (E_{pk} - E_{usable})c_{pk} + E_{std} \cdot c_{std} + \left( \left( \frac{E_{usable}}{\eta_{ch} \cdot \eta_{dis}} \right) + E_{opk} \right) c_{opk} \quad (6)$$

The total household savings  $SAV$  (£) are computed as:

$$SAV = \sum_{d=1}^T \sum_{k=0}^Y \frac{C_{day} - C_{day,BESS}}{(1+r)^k} \quad (7)$$

where  $d$  is the time index in days,  $T$  is the total number of days when the BESS is in operation,  $r$  is the discount rate, equals 3.5% [47], and  $Y$  is the total number of years when the BESS is in operation. The discount rate is defined as the rate of return that investors wish to earn when they provide capital at risk [48]. Finally, the payback time  $PB$ , in years, is measured when the total household savings reach the breakeven point with the cost of the BESS with second-life battery. Figure 2 shows the model flowchart summarising the procedure used in this study to find the payback time.

### 3 Results and Discussion

#### 3.1 Comparison of batteries from different vehicle models

The initial results from the mathematical model used the baseline data of Tab. 1, the electricity costs per period as shown in Tab. 2, and the daily electricity demand from integration of the profile shown in Fig. 1. The calculated payback time for the residential BESS with second-life battery is 8.3 years, with a total saving of around £2351 in 10 years or £330 after deducting the cost of the BESS. Then, the payback time based on the prices and capacities of

retired batteries of three fully battery electric vehicle (BEV) models and another PHEV, as shown in Tab. 3, were calculated and compared while keeping the other input data from the baseline condition (Tab. 1). The battery capacities were obtained from EV-Database [49] for the BEVs and Randall [50] for the PHEV. The battery cost was calculated using the battery pack price per kWh of each model given by König [51] with an additional 20% VAT added. If the pack price per kWh was not available for a specific model, the current battery price value of 216 £/kWh was assumed.

Figure 3 shows the BESS payback time based on the selected EV models of Tab. 3, calculated using the electricity consumption of a typical household in the UK obtained from integration of Fig. 1. The payback varies between 8.3 to 12.8 years, the lowest value provided by the Mitsubishi Outlander model, while the BEV models present payback time over 11.7 years. In general, these results are a direct reflection of the lower battery capacity of the PHEV models hence the low cost compared to BESS based on BEV batteries. It should be pointed out that some BEV models are available in a variety of configurations, for example, Tesla offers the Model 3 vehicle with a higher battery capacity of 75 kWh for an increased range. However, if the second-life battery from this vehicle was utilised as residential BESS, the payback would increase by around 29% compared to the standard range model with a 54 kWh battery (Tab. 3), thus making the BESS even more uneconomically viable. In any case, the long payback time obtained turn the application of BESS using second-life battery economically unattractive at the given conditions.

### 3.2 BESS capacity and associated costs

Using the current battery cost per unit of storage capacity, of 216 £/kWh, a simulation was performed to evaluate how the specification of second-life battery energy capacity in a

BESS regarding the residential daily electricity demand affects the payback time. The baseline conditions of Tab. 1 were used for the simulation, while the daily electricity demand was obtained from integration of Fig. 1. Figure 4 shows that, with a fixed battery cost per unit energy storage capacity, the payback time decreases rapidly with increasing BESS capacity until the point it can fully cover the electricity consumption during peak time, at around 0.5 ratio. Then, the payback time decreases less swiftly with increasing BESS capacity until reaching a minimum value of 7.7 years, where the BESS capacity reaches the size to attend all daily electricity consumption outside the off-peak period. With continuous increase of BESS capacity from this point the trend is inverted, with rising payback time. These results reveal that, to attain the minimum payback time, the BESS using second-life battery should be tailored to meet the peak and standard periods.

Figure 5 presents the total saving for a residential BESS lifetime of 10 years according to the ratio of BESS capacity to daily electricity consumption, assuming a fixed battery cost per unit energy storage capacity. Before deducting the BESS cost, the total saving in 10 years rises with increasing BESS capacity until about £3100 for the simulated conditions. This is the point where the BESS capacity meets the standard and peak electricity demand. Then, the total saving remains unchanged regardless of any increase in BESS capacity. This behaviour has a negative impact on the total saving after deducting the BESS cost for systems using batteries with larger capacity than necessary to attend the standard and peak electricity demand as increasing BESS capacity also increases its cost. After deducting the BESS cost, the maximum saving for a 10-year period of BESS operation at the simulated conditions is £562 when the BESS is sized to attend the peak and standard period for most of its life. Considering the initial cost of the optimised BESS system was about £2480, this corresponds to an investment with a yearly performance of approximately 2.1%. This may not look attractive enough to customers,

meaning that other measures are necessary to increase the saving and deploy the use of residential BESS systems based on second-life EV batteries.

Figure 6 shows the relationship between the BESS purchase cost and the payback time calculated using the electricity consumption of a typical UK household. The BESS is based on second-life batteries from five different EV models. The payback time drops linearly as the BESS is increased from the low-capacity sizes, in the region where the PHEV batteries are located, until reaching a minimum value where the BESS capacity meets the peak and standard electricity demand. This point occurs at the BESS cost of approximately £2400 and payback time of 7.7 years at the simulated conditions. This reveals that having a BESS with low initial cost but undersized to attend the peak and standard electricity demand does not necessarily translate to a short payback time. As the BESS size and cost are increased beyond the point where it meets the standard and peak electricity demand, the region where the BEV batteries are situated, the payback time linearly increases.

The BESS cost is directly affected by the battery price, which is the main variable to influence the payback time, but there is an expectation that EV battery prices will keep dropping in the years to come [52], driven by an increase in EV market share, advances in the manufacturing process and the use of more cost-effective materials [53]. However, for EV prices to be competitive against internal combustion engine (ICE) vehicles, the battery cost should be below 125 \$/kWh [54], a cost target that can be reached by 2022-2025 [55]. If this expectation is achieved and repurposed batteries have their costs reduced at the same proportion, a residential BESS using a second-life battery sized as that of a Mitsubishi Outlander PHEV model can have its payback time reduced from 8.3 to 6.9 years. Similarly, a BESS using a second-life battery with size like the one of a Tesla Model 3 would have the payback time reduced from 11.1 to 8.6 years.

From Fig. 1 and the results shown by Figs. 4 to 6, it can be assumed the optimum BESS capacity for an average UK household as determined by the minimum payback time and maximum saving in 10 years operation is 17.8 kWh. A BESS with this capacity can use a battery size close to the one equipping the first-generation Nissan Leaf, an EV model largely found in the UK with a 24-kWh battery [56]. This model units are coming near to their end of life in the next few years, and, with the right incentives, their second-life batteries would make a suitable choice to be used as residential BESS. If a second-life battery from this EV model is repurposed as BESS in an average UK household it will have a payback period of 7.8 years, assuming a current battery price value of 216 £/kWh. As a consequence of decreasing battery prices, EV battery capacity is increasing with the introduction of new generations of each vehicle model [57] thus allowing increased range and fast charging to overcome range anxiety. For example, the current generation of Nissan Leaf is offered with a base capacity of 40 kWh, a 66% increase from the previous generation, similarly to the Renault Zoe model (see Tab. 3). Likewise, for PHEV models, the previous BMW 330e had a 7.6 kWh battery compared to 12 kWh for the current one [58] while the next generation of Mitsubishi Outlander was announced to have a larger battery size up to 20 kWh for increased range [59]. Therefore, due to the suitability of their capacity range, second-life PHEV batteries are preferable choices to BESS to attend the average UK household compared with the ones of BEV models.

### **3.3 Peak and off-peak rate effects**

The results of Figs. 4 to 6 assume the residential household uses a three-rate tariff (Tab. 2), however, nearly 80% of UK households pay electricity bills using a flat unit rate while 18% fall under the Economy 7 category [60]. Economy 7 is a tariff that gives consumers cheaper electricity for 7 hours each night, but they have to pay a high price for electricity usage during



the day [61]. The electricity unit rates equal £0.174 per kWh for flat unit rate and Economy 7 day and night equal £0.206 per kWh and £0.099 per kWh, respectively, taken from [62]. Therefore, for the average household in the UK moving from a flat rate to a three-rate tariff with the baseline BESS, their total saving for 10 years will be around £621 after deducting the BESS cost, while the payback time will be 7.2 years. Similarly, switching from Economy 7 to a three-rate TOU tariff will save £1110 in 10 years using the baseline BESS, with a payback time of 5.9 years.

BESS are designed to operate with the battery providing electricity to the residence during peak and standard periods, when the unit rates are higher, and charged during the off-peak period, at a much lower unit rate (see Tab. 2). A simulation was carried out with fixed peak and standard unit rates and variable off-peak unit rates to evaluate how the off-peak rate affects the payback time. Figure 7 shows that the payback time substantially changed with larger differences between peak and off-peak electricity unit rates. The limiting condition is obtained when the off-peak unit rate is entirely reduced to £0.00 for a maximum rate difference of £0.30 compared to the peak unit rate, representing an application of subsidised off-peak electricity unit rate. In this case the payback time is minimised to 4.9 years, causing to a deep reduction of 41% to the baseline payback time of 8.3 years, and may largely contribute to turn residential BESS economically attractive. The opposite occurs if the off-peak unit rate reaches a value equal to the current Economy 7 night-time rate of around £0.20 difference from the peak unit rate, making the payback time rise to 13.1 years thus exceeding the BESS projected lifespan. Other authors [17] also reported that larger differences in tariffs reduced the payback time, using different unit rates from the ones used here. These findings highlight the importance of low off-peak unit rates to make residential BESS with a three-rate tariff a viable option for consumers.

In a recent response to smart charging policy consultation, the government highlighted the intention to mandate for smart chargers to have the capability to offer users a charging schedule with a default setting that prevents EVs from charging at specified peak hours [63]. These standard peak times will be stated in the legislation as 8 am to 11 am and 4 pm to 10 pm to avoid any significant implications of increased demand that require additional investments in the electricity network and generation capacity. Updating the mathematical model to reflect the peak periods in this proposal will reduce the BESS payback to 4.9 years for the average household due to the increased amount of energy initially covered during peak times without BESS, assuming the EV is charged during off-peak times. This analysis reveals that, if the peak period is extended to cover additional times during the day, the high electricity consumption between 4 pm to 10 pm (Fig. 1) will make a residential BESS using second-life battery more economically feasible.

### **3.4 Monthly electricity consumption and potential BESS savings**

Figure 8 shows the seasonal variability in electricity consumption for a typical household in the UK [46]. During cold months the total electricity demand shows a significant increase, mainly due to the rise in consumption during peak and standard periods. The average daily saving in 10 years of operation for each month was calculated using the baseline data (Tab. 1). Figure 9 shows the changes in average daily saving between each month during the 10 years of using BESS, reaching a 35% decrease from the month of maximum saving (December) to the month with the minimum daily saving (May). A simulation was performed to determine the shortest payback time if the BESS capacity is sized based on the daily electricity consumption of those months, to fully cover the peak and standard periods for 10 years of operation. If the BESS capacity is designed based on the daily electricity consumption

of December the resulting payback time is 9.8 years and, if the BESS is based on May consumption, the payback time becomes 8.3 years. While a December-based BESS capacity can attend the peak and standard electricity consumption for the whole year, increasing the total saving per year, the breakeven point is pushed further due to the higher BESS cost in comparison with the May-based one of lower capacity.

### 3.5 Household size influence

The above results were based on daily electricity consumption for an average household in the UK. However, electricity demand varies between different household sizes, as generally an increase in the number of occupants increases the cumulative energy consumption. The average household size in the UK is 2.4, with two people being most common and above five being the least common. Most families in the UK have two children, making a household with four people a good representative of an average family household [64]. Figure 10 presents the daily electricity consumption for each household size [46] and the percentage of electricity demand that occurred in peak, standard and off-peak time, based on Tab. 2, showing the increase in electricity consumption with an increase in the number of occupants.

A simulation was conducted to measure the payback time for different household electricity profiles taken from HES, using the baseline data (Tab. 1). Figure 11 shows that a single person household has the highest payback time of 12.4 years, exceeding the projected life of the BESS, and for a household with two people the payback time drops to 8.3 years. With a household of three people the payback time is 7.1 years and, for a larger number of household occupants, the change in payback time varies little between 6.5 and 6.8 years. These results suggest the adoption of residential BESS to be more economically feasible for households of three or more occupants. In the best possible scenario of having the BESS

designed to fit the standard and peak electricity consumption, battery cost dropped to the level where EVs reach the same price as equivalent ICE vehicles, and household with three occupants or over, the minimum payback time is reduced to 4.8 years. Subsidised off-peak rates can further decrease the payback time.

### **3.6 Sensitivity analysis**

A sensitivity analysis was performed concerning specific parameter impacts on BESS payback time, including battery cost, discount rate and cost of electricity. Figure 12 shows that doubling the discount rate from the baseline value of 3.5% (see Tab. 1) to 7%, the payback time increases from the baseline calculated value of 8.3 years to 9.7 years. The halving of the baseline discount rate decreases the payback time to 7.7 years. The doubling of the overall electricity unit rates or peak time lowers the payback time to around 3.7 years, as the difference between peak and off-peak tariffs increases, making the BESS more justifiable with higher savings. Increasing the standard electricity tariff by 100% lowers the payback time to 5 years, while reducing the standard electricity tariff by 50% raises the payback time to 11.7 years. The BESS would become more economically feasible with lower off-peak electricity costs, reaching a payback time of 6.1 years at 50% of the baseline tariff. The application of a similar analysis shows that increasing the cost of a repurposed battery from 20% to 40% of the cost of a new battery leads to an increase in the payback time from 8.3 to 11.7 years.

### **3.7 Concluding remarks**

In summary, the results show that a correctly sized BESS to meet the peak and standard period demand achieves the highest saving in 10 years and the lowest payback time of 7.7

years. Therefore, a BESS with a low initial cost does not directly translate to a short payback time if the capacity is undersized below the peak and standard electricity demand. A drop in battery price by 46% from the current level would reduce the payback time of BESS from 8.3 to 6.9 years for BESS based on Mitsubishi Outlander PHEV battery size, or from 11.1 to 8.6 years with a battery of Tesla Model 3.

The payback time of BESS using a second-life battery equals 7.3 years for an average household in the UK, shifted from a flat rate to a three-rate tariff. The differences between peak and off-peak electricity unit rates significantly impact BESS payback time. For example, a completely subsidised off-peak electricity unit rate would drop the payback time from 8.3 to 4.9 years. However, increasing the off-peak rate to equal value of the Economy 7 night-time rate raises the payback time to 13.1 years. Extending the peak period until 10 pm and including morning peak hours between 8 am to 11 am reduce the BESS payback time to 4.9 years. The payback time varies from 6.5 years for households above five occupants to 12.4 years for single-person households, impacted by the difference in electricity demand profile.

A possible alternative to the adoption of BESS is public adherence to TOU tariffs. The introduction of TOU tariffs can impact residential electricity consumers differently, depending not only on the financial aspects but also on time availability [65]. Several trials show low engagement levels in TOU tariffs regarding consumer behaviour. Modelling changes in behaviour is challenging as it requires data currently unavailable [66]. The results from the model here presented did not consider changes in consumer behaviour with TOU tariffs.

## **4 Conclusion**

A mathematical model was developed and applied to second-life batteries of five different EV models, using current battery prices and electricity unit rates, resulting in

calculated payback time ranging from 8.3 to 12.8 years. At the simulated baseline conditions, the minimum payback time of 7.7 years is achieved when the BESS is designed to attend peak and standard electricity period. The most economical options for a second use of EV batteries as BESS for electricity load levelling in the residential sector are the small capacity units found in first generation BEV or current and future PHEV models. From the results obtained by the model simulations, the following recommendations are made to reduce the payback time and turn the adoption of residential BESS more economically attractive:

- Rightsizing the BESS to attend the peak and standard electricity demand
- BESS adoption in households of three or more occupants
- Application of subsidies to off-peak electricity unit rates

In the best possible scenario of having combined the BESS capacity rightsized to attend the peak and standard electricity demand, application to a household of three or more occupants, and battery price dropped to the level where EVs match equivalent ICE vehicle price, the shortest payback time of 4.8 years is achieved. Further reduction of the payback time can be attained with subsidised off-peak electricity.

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## Nomenclature

### Abbreviations

BESS	Battery Energy Storage System
BEV	Battery Electric Vehicle
BMS	Battery Management System
DOD	Depth of Discharge
ESS	Energy Storage System
EV	Electric Vehicle
HES	Household Electricity Survey
ICE	Internal Combustion Engine
PHEV	Plug-in Hybrid Electric Vehicle
SOC	State of Charge
SOH	State of Health
TOU	Time of Use
UK	United Kingdom

### Symbols

$C_{bat}$	Used battery purchase cost (£)
$C_{BESS}$	Total cost of the BESS (£)
$C_{bms}$	Price of the BMS (£)
$C_{day}$	Daily cost of electricity consumption without BESS (£)
$C_{day,BESS}$	Daily cost of electricity consumption with BESS (£)
$C_{opk}$	Off-peak electricity unit rate (£/kWh)
$C_{pk}$	Peak electricity unit rate (£/kWh)



$c_{std}$	Standard electricity unit rate (£/kWh)
$d$	Time index (Days)
$E_{bat}$	Used battery capacity (kWh)
$E_{day}$	Total daily electricity consumption (kWh)
$E_{opk}$	Consumption during off-peak period (kWh)
$E_{pk}$	Consumption during peak period (kWh)
$E_{std}$	Consumption during standard period (kWh)
$E_{usable}$	Usable battery capacity (kWh)
$k$	BESS operation time (Years)
$PB$	Payback time (Years)
$r$	Discount rate (%)
$SAV$	Total household saving (£)
$SOH_i$	Initial state of health (%)
$T$	Total number of days in operation (Days)
$Y$	Total number of years in operation (Years)
$\alpha_{deg}$	Degradation rate per year (%/year)
$\beta_{DoD}$	Used battery DOD (%)
$\beta_{inst}$	Installation cost percentage (%)
$\eta_{ch}$	Charging efficiency (%)
$\eta_{dis}$	Discharging efficiency (%)

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Table 1. Baseline model input data.

INPUT PARAMETERS	VALUE	UNIT
Battery energy capacity when new	13.8	kWh
Initial state of health	80	%
New battery purchase cost	2981	£
Retired battery purchase cost	596	£
Battery depth of discharge	60	%
Degradation rate per year	2.8	%
Charging efficiency	90	%
Discharging efficiency	90	%
Discount rate	3.5	%

Table 2. Electricity tariffs time and rate.

TARIFF	TIME PERIOD (h)	ELECTRICITY UNIT RATE (£/kWh)
Off-peak	00:00 – 07:00	0.064
Standard	07:00 – 16:00, 20:00 – 00:00	0.140
Peak	16:00 – 20:00	0.300

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Table 3. Specifications of selected vehicle models.

VEHICLE MODEL	POWERTRAIN CONFIGURATION	NEW BATTERY COST (£)	NEW BATTERY CAPACITY (kWh)	RETIRED BATTERY COST (£)	RETIRED BATTERY CAPACITY (kWh)
BMW 330e	PHEV	2592	12	518	9.6
Mitsubishi Outlander	PHEV	2981	13.8	596	11
Renault Zoe	BEV	9737	44.1	1947	35.3
BMW i3	BEV	11394	42.2	2279	33.8
Tesla Model 3	BEV	9396	54	1879	43.2

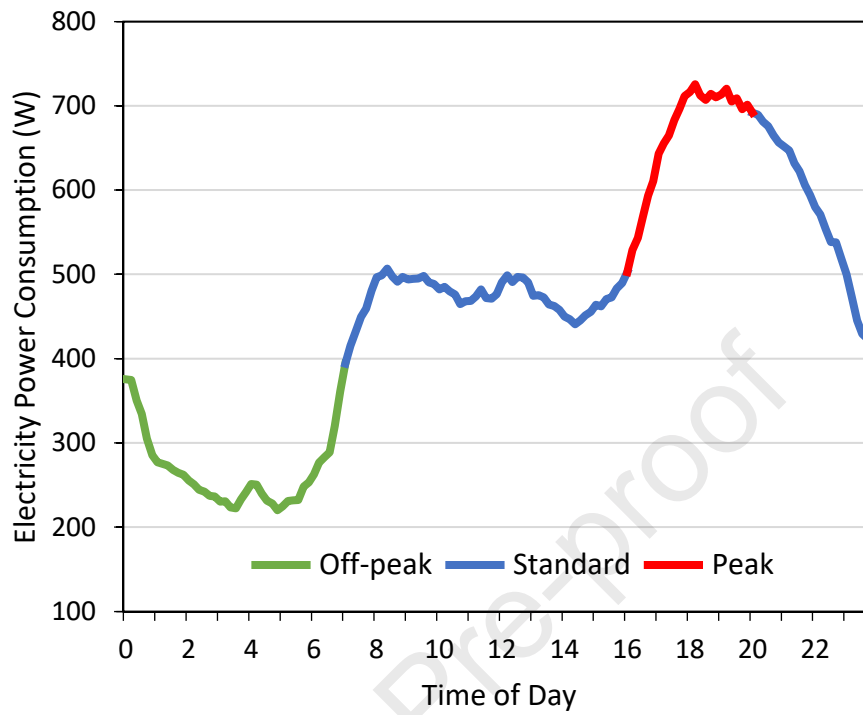


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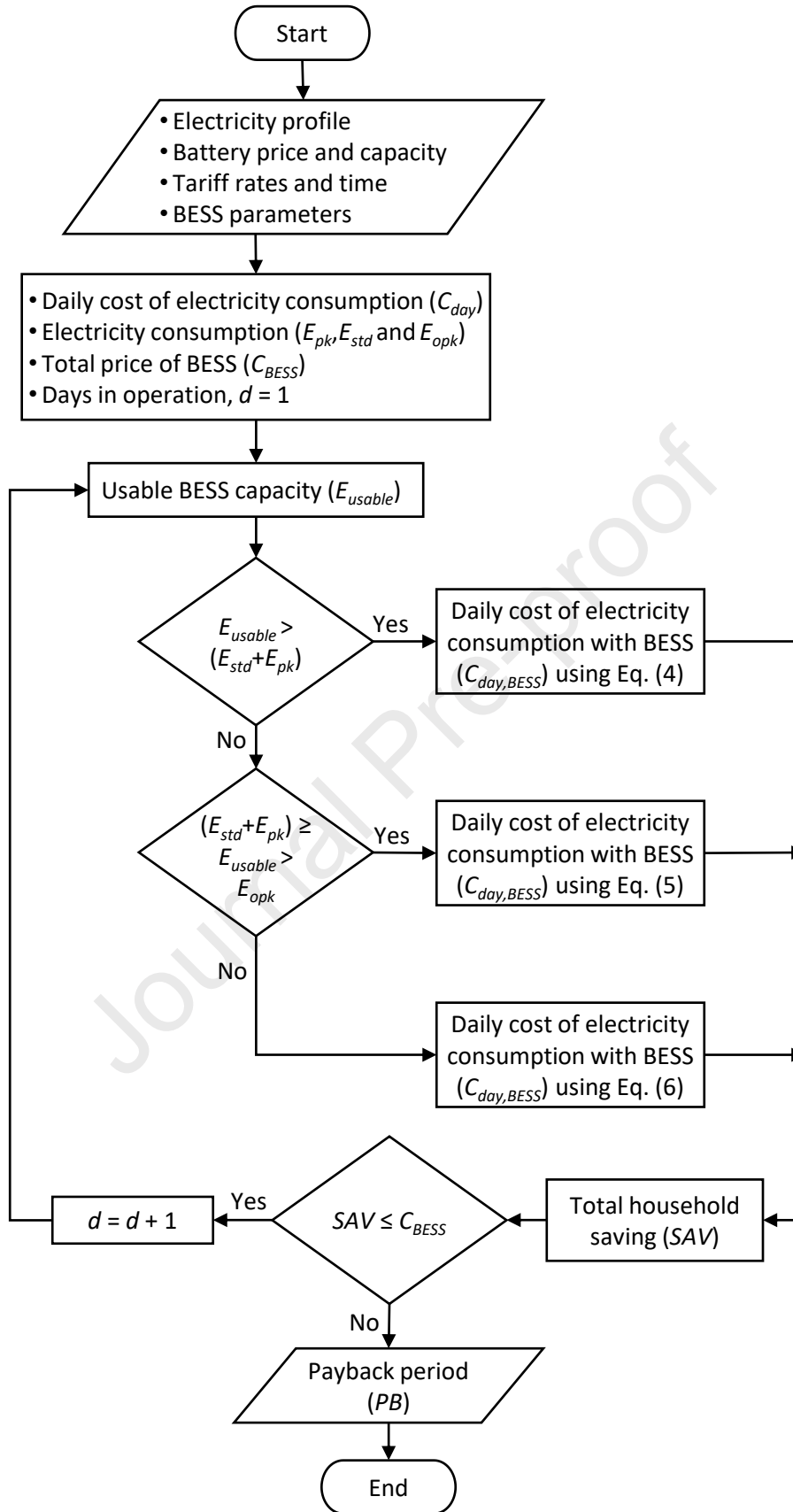


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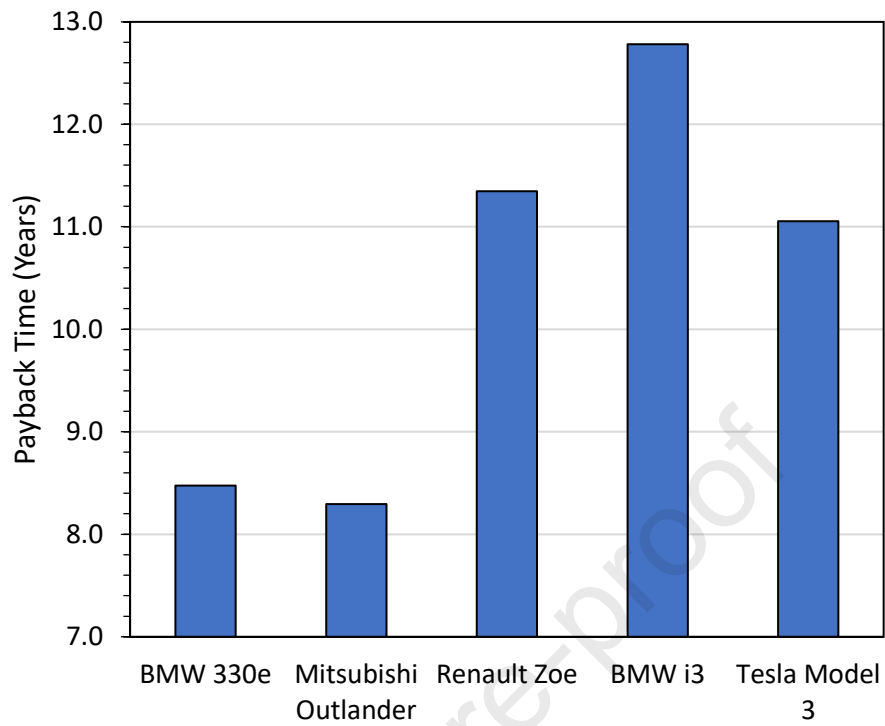


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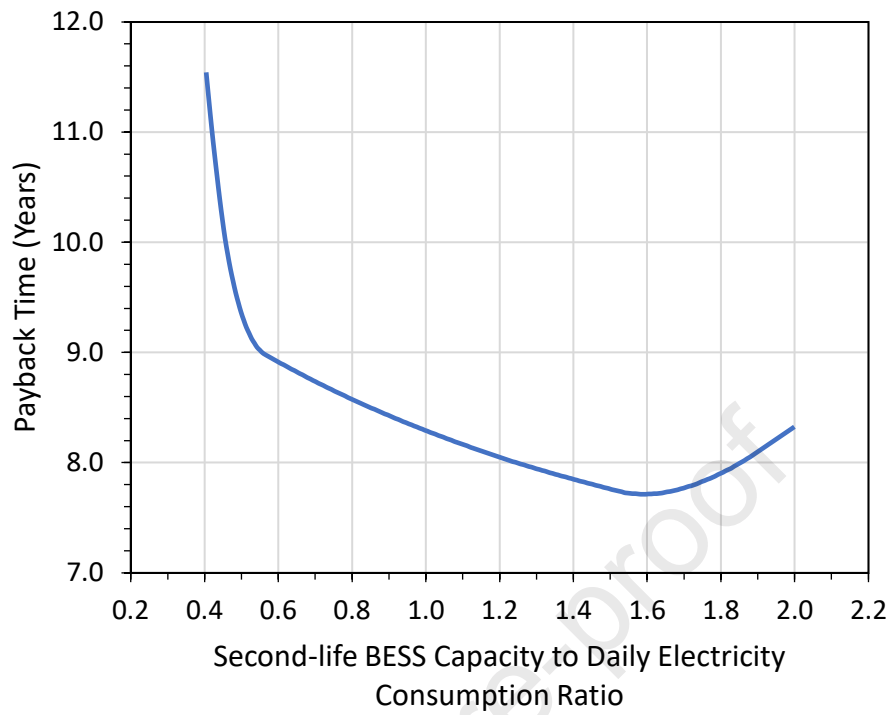


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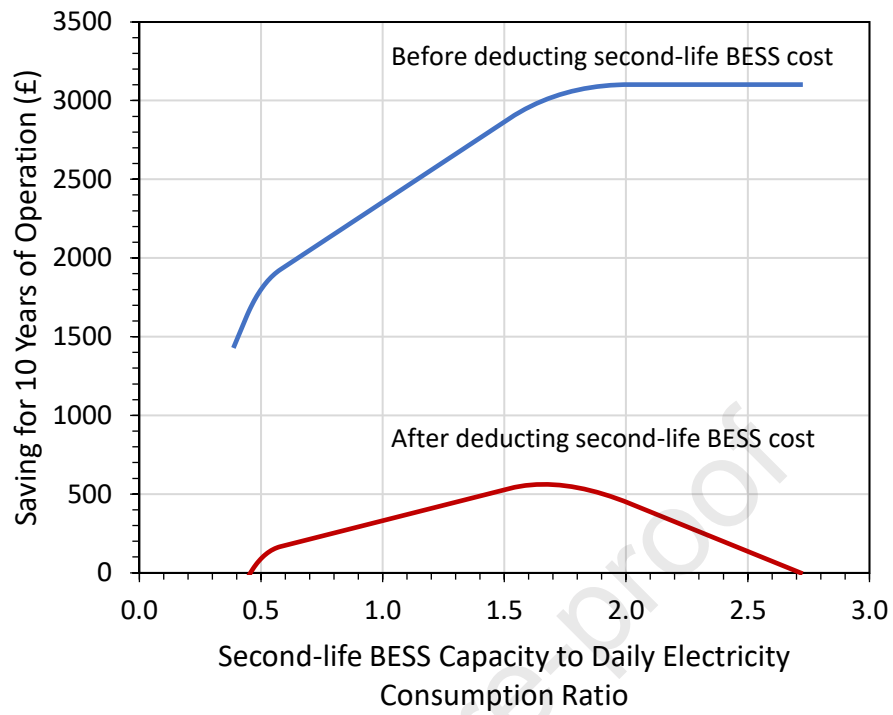


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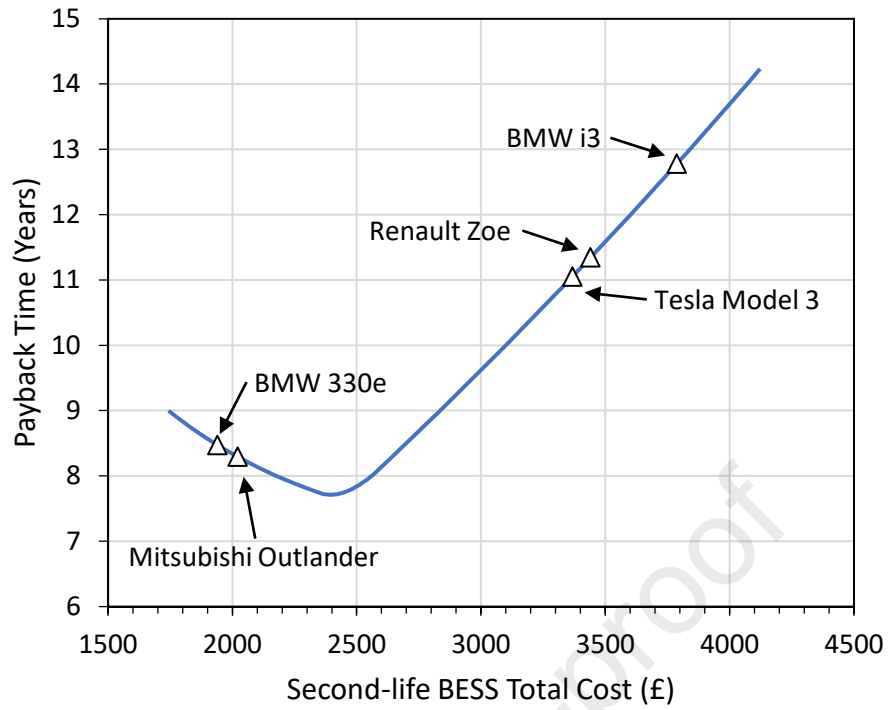


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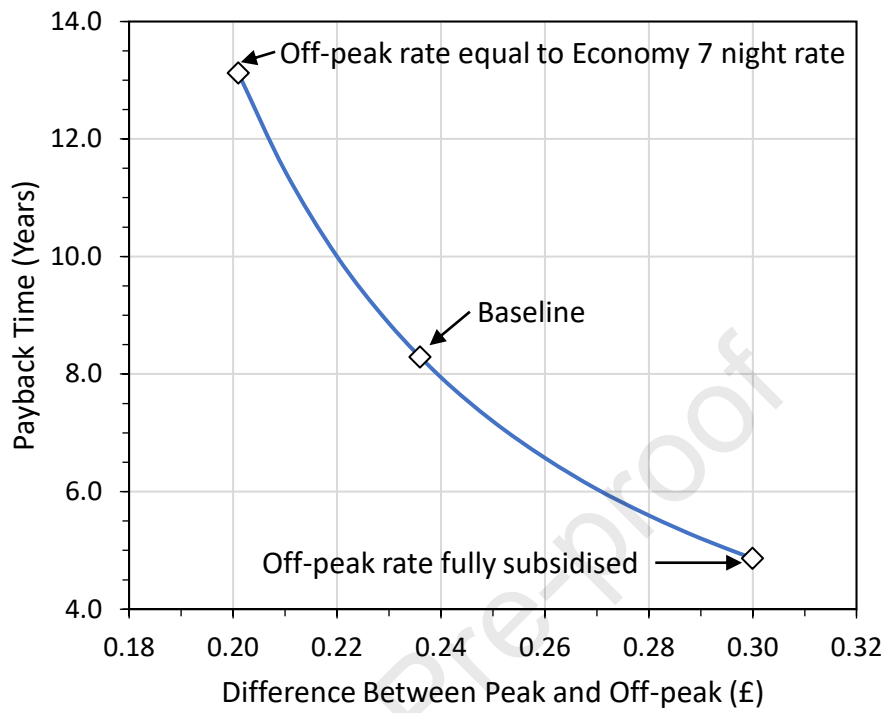


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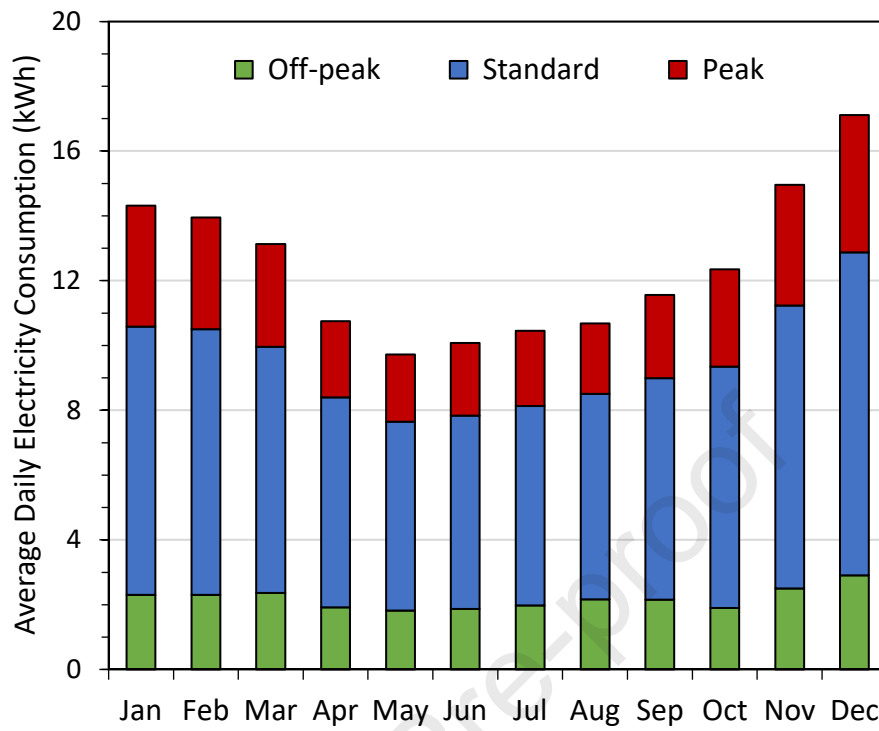


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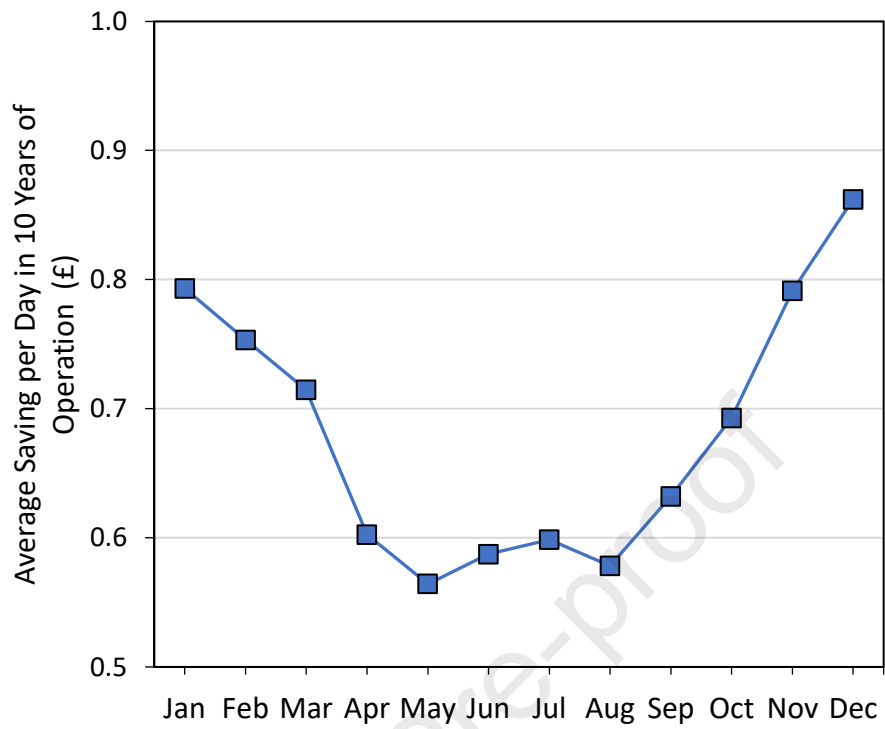


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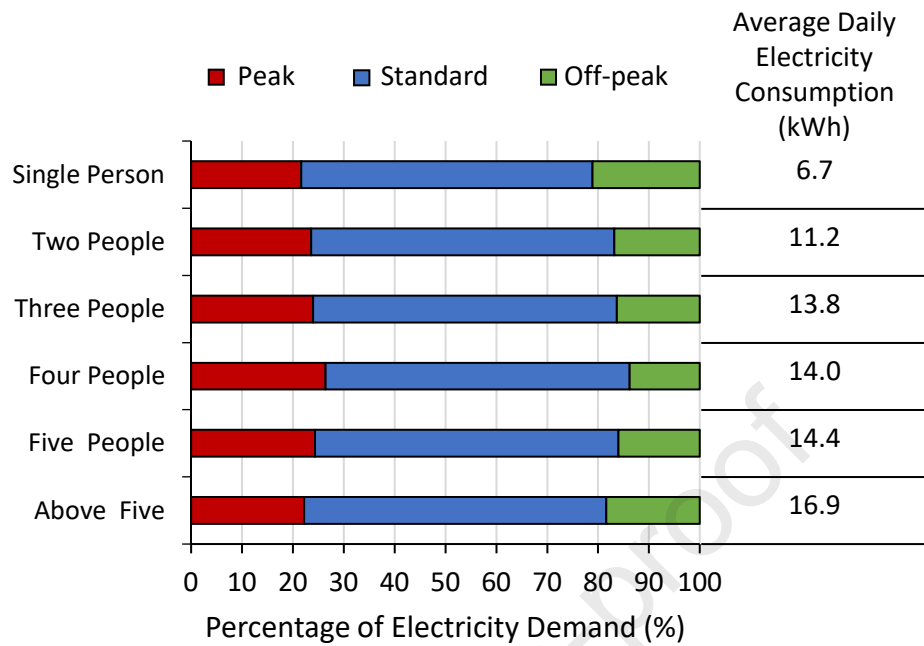


Figure 10. Electricity consumption for different household sizes in the UK and the percentage of demand occurred in peak, standard and off-peak time [45].



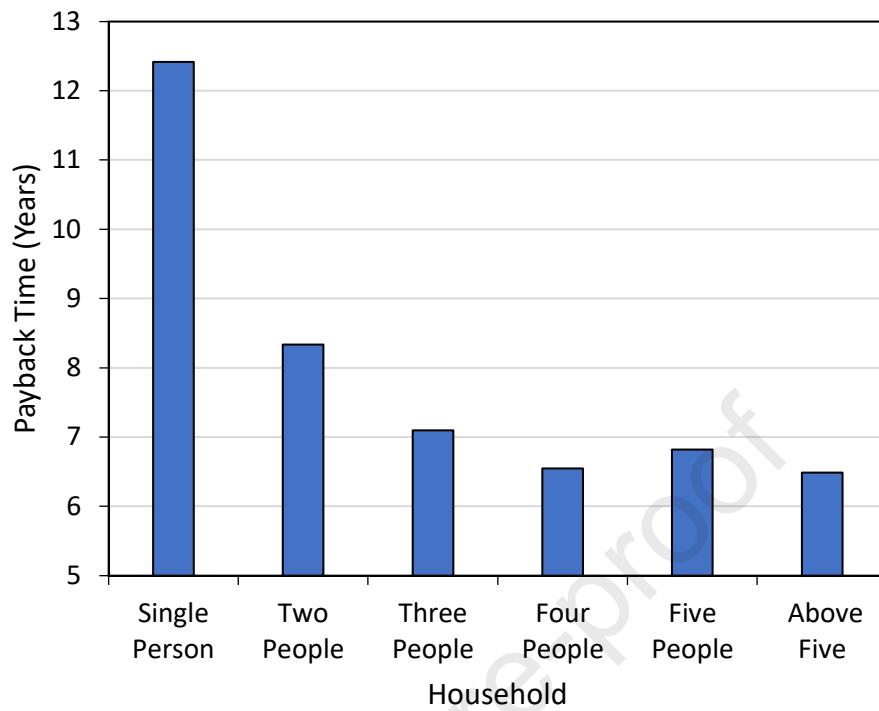


Figure 11. Payback time for different household size with baseline BESS, based on electricity consumption during peak, standard and off-peak periods.

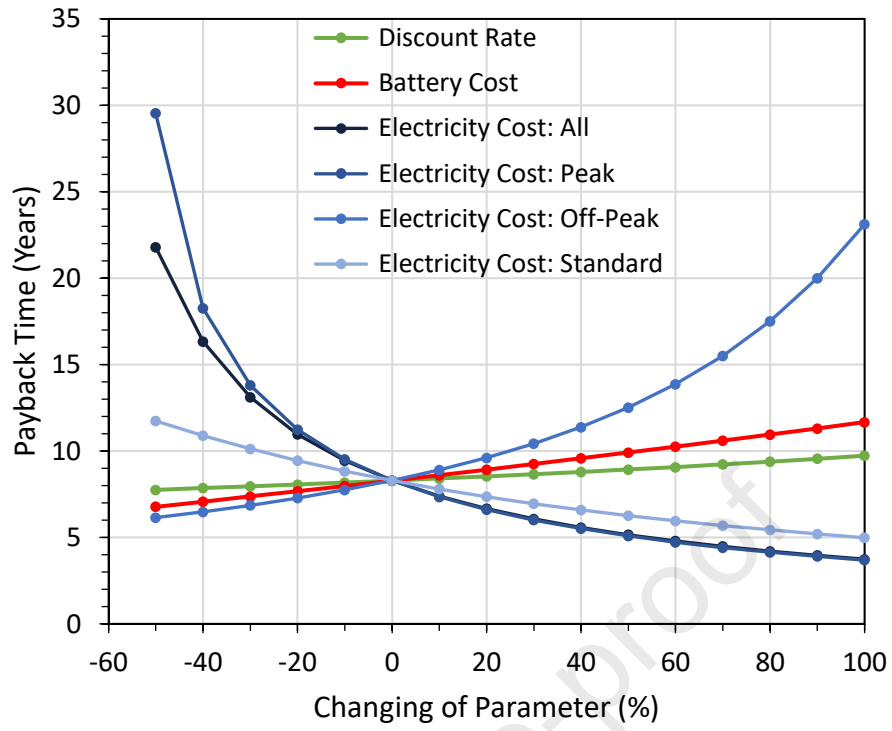


Figure 12. Sensitivity analysis results.

## RESEARCH HIGHLIGHTS

- Storage systems with electric vehicle retired batteries show over 7 years payback time
- Plug-in hybrid vehicle batteries are the most ideal for residential energy storage
- Battery rightsizing, price drop and use by three households produce best scenario
- The payback time in the most favourable simulated scenario is reduced to 4.8 years
- Subsidised off-peak electricity unit rate can further reduce payback time

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**Declaration of interests**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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