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Impact of Second Life Electric Vehicle Batteries on the Viability of Renewable Energy Sources

Michael J. Knowles[1*] and Adrian Morris[2]

[1]Department for Computing, Engineering and Technology, University of Sunderland, St Peters Way, Sunderland, UK.
[2]Institute for Automotive and Manufacturing Advanced Practice (AMAP), University of Sunderland, The Industry Centre, Colima Avenue, Sunderland, UK.

Authors' contributions

This work was carried out in collaboration between all authors. Author MJK participated in the data capture and development of the model, as well as preparing the initial draft of the manuscript. Author AM participated in experimental design, data analysis and redrafting of the manuscript. All authors read and approved the final manuscript.

Research Article

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ABSTRACT

Aims: To investigate the viability of using second life electric vehicle batteries as 'buffer packs' for localized, in home storage of renewable energy. To investigate the potential value of such energy storage in terms of reducing energy bills. To investigate the effect, if any, of social group on energy demand patterns and the subsequent effect on buffer packs.
Methodology: Energy data was collected from 15 households and a representative daily demand pattern was formed from each. The availability of solar power was calculated based on standard assumptions regarding UK household installations. The flow of energy between the supply grid, renewable sources (i.e. solar panels) and a 10kWh battery storage system (the 'buffer pack') were simulated on a minute by minute basis allowing the savings in power drawn from the grid to be calculated.
Results: The simulation has indicated that the use of buffer packs has the potential to greatly increase the utilization of locally generated renewable energy. In some cases the stored energy removed the need to draw any power from the grid. The value of energy storage of this type has been estimated at approximately £250.
Conclusion: Buffer packs have substantial potential to increase the degree of utilization of renewable energy sources. However the financial viability of such systems remains questionable, even when utilizing second-life electric vehicle batteries. Further work is

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**Corresponding author: E-mail:Michael.Knowles@sunderland.ac.uk;*

recommended to address some of these issues and, in particular, to investigate the effects of seasonal variations in energy use and renewable energy availability on buffer pack applications.

Keywords: Renewable energy; solar photovoltaic power; electric vehicles; batteries.

1. INTRODUCTION

Electric vehicles are seen as a key technology for reducing the carbon emissions produced by road transport [1-3]. New models such as the Nissan Leaf and the Renault Twizy are now entering the market which have been designed and engineered for electric traction rather than being converted from conventional vehicle designs. While the uptake of these vehicles has not reached the targets hoped for governments are still providing substantial investment in incentives [1,4] and infrastructure [3].

EVs mostly utilise battery packs based on lithium ion technology. Lithium Ion batteries have the advantages of having favourable energy density, up to 800 Wh/L [5], low self-discharge and low memory effect. The major disadvantage of lithium ion batteries is their cost relative to that of other battery types [6,7]. For this reason the lifespan of the battery and its second-hand value is a critical factor in the whole life cost of an EV. It is generally accepted that an EV battery is no longer fit for purpose when its capacity has dropped to 80% of its original value[8,9], this value having been proposed by the US Advanced Battery Consortium [10]. Battery packs which are subsequently removed from EVs are, however, still capable of storing substantial and potentially useful amounts of energy in alternative applications and as such may offer better value in a second-life application than through stripping of materials for manufacturing new cells.

One potential second-life application for EV batteries which has been proposed is for in-home buffer packs to maximise the utilisation of domestically generated renewable energy. Renewable energy has proved attractive to many due to environmental, economic and political concerns regarding alternatives such as nuclear and fossil fuels. For this reason many governments have provided incentives to renewable energy sources. The UK Government, for example, has offered the Feed-In Tariff scheme under which Solar Photovoltaic capacity has increased from 77MW in 2010 to over 1500MW by late 2012[11].

One of the major drawbacks for domestically produced solar energy is misalignment between the time of day when the energy is produced and the time when the energy is needed. Solar photovoltaic (PV) panels convert sunlight directly into electricity and are one of the most likely technologies to achieve widespread domestic uptake due to the ease of installation on rooftops of existing properties. The downside to PV technology is that it produces energy through daylight hours and reaches its maximum output in the middle of the day. Many households, however, are empty at this time and as such have low energy requirements during this period. One potential solution which has been proposed is to return energy to the grid for industrial use. Current grid infrastructure is not, however, designed to support such power flows and as such substantial investment will be required if renewable uptake is to increase. By using batteries in the home to store energy produced when demand is low for use later infrastructure upgrade costs can be eliminated.

In this paper the potential impact of in-home buffer packs consisting of second life EV batteries will be investigated using data gathered a selection of households. The monetary value of the energy stored will be used to form an estimate of the potential value of such a buffer pack. This will support the evaluation of lifecycle cost for EVs.

The remainder of the paper is structured as follows. In the following section the technology and degradation mechanisms relative to EV batteries are outlined. The nature of commonly used domestic renewable energy sources is considered in section 1.2. The data captured for this study is described in section 2.1 which is followed by details of the modeling which is carried out. A summary of the results is then presented which includes a high level economic assessment of such an application of second life batteries. The paper is completed with conclusions, discussion and recommendations for future work in this area.

1.1 Electric Vehicle Batteries

The key technological development which has led to the viability of batteries as a power sources for vehicles is the development of the lithium ion cell which provides sufficient energy density for a small car to have adequate range. These improvements have also enhanced the development of hybrid vehicle technologies where batteries are used to store energy captured during braking to reduce fuel use. Lithium ion cells consist of a lithium-based negative electrode and a transition metal oxide for the positive electrode, separated by an electrolyte. During discharge lithium ions move across the electrolyte to form a lithium metal oxide at the positive electrode, a process which is reversed during charging[6,7]. Table 1 illustrates some common battery capacities in electric vehicles.

Table 1. Battery Capacity for a range of electric vehicles

Vehicle	Battery capacity
Nissan Leaf	24 kWh
Chevrolet Volt	16kWh
Toyota Prius (Plug-in)	4.4kWh
Mitsubishii Miev	16kWh
Renault Twizy	7kWh
Renault Fluence Z.E.	22kWh
Smart E.D.	16.5 kWh

While improvements in energy density have made EVs viable in terms of range, there is little spare capacity available in most EV batteries to allow for degradation. Battery degradation is a well-researched topic and is caused by a number of mechanisms including the formation of a resistive layer on the cell electrodes called a Solid Electrolyte Interface (SEI) [12,13] which reduces the amount of lithium available for energy storage. A battery capacity of 80% of initial capacity has been determined to be the maximum level of degradation which can be tolerated before a battery is deemed no longer suitable for vehicle use[8-10]. After this point a battery must be replaced if the vehicle is to have enough range to remain useful. Several factors are known to affect battery lifespan including depth of discharge between charges [14], the use of high current ‘fast’ charging systems [15] and the drawing of power at a high rate under harsh acceleration [16].

One of the key determining factors in battery economics is expected to be potential second life applications for EV batteries once their capacity has degraded. One potential application which has been identified is the use of these batteries for smoothing the load on the electric power grid [17]. One of the key difficulties in managing the domestic power grid is accounting for the daily patterns of power use. Adjusting the rate at which power is generated to account for variations in demand is problematic. As such the use of batteries to smooth such variations offers a potential market for former EV batteries which no longer have the necessary capacity to weight ratio for mobile applications. One area of particular interest is to enable the more effective and localised use of renewable power.

1.2 Renewable Energy Sources

Renewable energy production has received substantial uptake in recent years due to concerns regarding carbon emissions, energy security and cost increases for fossil fuels. Large scale installations have been dominated by wind turbines with nearly 4000 turbines installed onshore in the UK and a further 900 offshore[18]. At a domestic level solar power has been most widely adopted since it is suited to installation on the roof of many homes and is less prone to local obstacles reducing output than small scale wind power, which is susceptible to unpredictability and which is extremely site specific in terms of its viability[19].

Domestic solar power takes two forms. Solar energy can be used to heat water or to produce electricity directly using photovoltaic panels. While solar installations for heating water have been available for a number of decades and are the most commonly used domestic renewable energy source [19] solar PV has begun to receive attention due to recent improvements in its effectiveness [20,21].

One of the major issues with PV solar panels is time of day during which energy is produced which varies with the power delivered by the sun. This does not conveniently align with the requirements of many households. Thus systems which can buffer energy until it is needed are potentially extremely beneficial since the likely ongoing prevalence of solar power as a domestic energy source means the potential impact is substantial. Domestic generation is particularly attractive since it minimizes the need for extensive modifications to distribution infrastructure.

2. METHODOLOGY

One of the potential second life applications of electric vehicle batteries is for creating small scale localized energy buffering within the home. This will allow energy produced by renewable sources to be stored until it is needed in the home. There are several advantages to this approach. Firstly this will allow the availability of renewable energy sources to be matched to the demand exhibited by many users. This in turn reduces the need to sell excess energy produced during periods of low demand back to the grid, reducing this load on the available infrastructure as well as reducing transmission losses. Furthermore the stored energy can be used at peak demand to reduce load placed on the infrastructure at such times.

In order to investigate this phenomenon a simulation of energy generation, storage and consumption using such a system has been carried out. Solar power has been selected since this is the most likely renewable energy source to be installed in a domestic setting. A set of energy demand profiles has been collected for various households using smart metering equipment. A mathematical model is then used to ascertain the potential for energy storage through the day. Further details on the methodology are provided in the subsequent sections.

2.1 Data Capture

Smart meters are seen as an important tool for households to reduce their energy consumption. Such devices provide users with instantaneous and cumulative information regarding the rate at which energy is being consumed and the expenditure accrued on that energy. Information is typically provided via an In-Home Device (IHD)(Fig.1). Many energy suppliers are providing smart meters and the UK government has made the installation of Smart Meters compulsory by 2020 [22].

Fig. 1. IHD of the type used in this study

The data which will be used in the present study was collected as part of the Changing Home Electrical Energy Requirements (CHEER) project [23]. The objective of CHEER was to capture data on the effects of installing smart meters on domestic energy consumption. Fifteen households received OWL Smart Meters, as illustrated in Fig. 1, for two 10 day long measurement periods. The participants were divided into three groups:

- Elderly Couples
- Couples with no Children
- Families

The data captured is in the form of average power consumption across each one minute long sampling period during the entire survey. The data was subsequently processed to give average energy consumption at each minute of the day.

2.2 Renewable Energy Modeling

The first stage of the modeling work carried out involved determining the amount of sunlight available for conversion into energy. In order to achieve this, the PVGIS PV Estimation Utility was utilised to generate data on the amount of solar energy incident on a given location on Earth at a given time of year [24]. This model is a web based tool developed by the European Commision Joint Research Centre Institute for Energy and Transport. The tool provides estimates for incident solar energy at a specified location. The location specified was near Sunderland in North East England. The parameters used in the model are given in Table 2.

Table 2. Parameters used in solar model

Parameter	Value
Location	54°53'48" North 1°23'43" West
Elevation	0 metres
Inclination	35°

The result of the model is the incident solar energy in W/m^2 for the specified location at a given angle of inclination. An inclination angle of 35° has been selected as this is typical for roof inclination in the UK. The data is specified in one minute intervals. The solar energy incident varies during the year due two factors related to the orbit of the Earth around the sun. Firstly the duration of daylight hours varies during the year. Secondly the average power of incident daylight is reduced during the winter due to the tilt of the earth. This is illustrated in Table 3.

Table 3. Summary of output of solar power model

	Average incident energy during daylight hours(W/m^2)	minutes of sunlight	daily incident energy (kWh)
January	153.6	560	1.43
February	210.6	720	2.53
March	252.8	880	3.71
April	278.1	1080	5.01
May	292.4	1240	6.04
June	271.4	1320	5.97
July	281.5	1280	6.01
August	281.2	1120	5.25
September	273.5	960	4.38
October	207.8	800	2.77
November	167.3	600	1.67
December	108.1	520	0.94
Average	**232**	**923**	**3.8**

In order to determine the amount of power it is possible to produce using solar panels it is necessary to multiply the incident power by the area of the solar panel and the conversion efficiency of the panels. For the purpose of the modeling performed herein a value of 16 m^2 is used as typical area available for solar conversion. An efficiency of 20% is assumed based on the current efficiency of solar cells(of the order of 15%) and potential improvement in the coming years [20].

2.3 Model of Energy Storage Strategy

The surplus power $P_{surplus}$ is defined as the difference between the amount of solar power produced, P_{solar} and that consumed $P_{consumed.}$

$$P_{surplus} = P_{solar} - P_{consumed} \quad (1)$$

The model utilises a step duration of 1 minute since this is the rate at which the energy consumption data is available. In order to simplify the model energy is measured in Watt minutes (Wm). Thus the resultant surplus energy $E_{surplus}$ is equivalent in value to $P_{surplus}$ when working in one minute intervals. The State of Charge (*SoC*) of the battery is modeled based on the energy flow derived from the surplus power $p_{surplus}$.

$$\Delta SoC = SoC_t + \frac{E_{surplus}}{E_{Capacity}} \tag{2}$$

$$SoC_{t+1} = \begin{cases} \Delta SoC & 0\% \leq \Delta SoC \leq 100\% \\ 100\% & \Delta SoC > 100\% \\ 0\% & \Delta SoC < 0\% \end{cases} \tag{3}$$

Where $E_{Capacity}$ represents the energy storage capacity of the battery. Three distinct scenarios exist in terms of power drawn from the grid, P_{grid}. If the solar power produced exceeds the power consumed i.e. $P_{surplus}$ is positive:

$$P_{grid} = 0 \tag{4}$$

If the solar power produced is unable to satisfy the consumption, i.e. $p_{surplus}$ is negative, but the battery has adequate power stored to completely meet the shortfall:

$$P_{grid} = 0 \tag{5}$$

If there is insufficient solar power and the battery is not able to meet the shortfall:

$$P_{grid}=P_{consumed} - SoC \text{ x } E_{Capacity} \tag{6}$$

The function of the model is illustrated in the flow chart in Fig. 2.

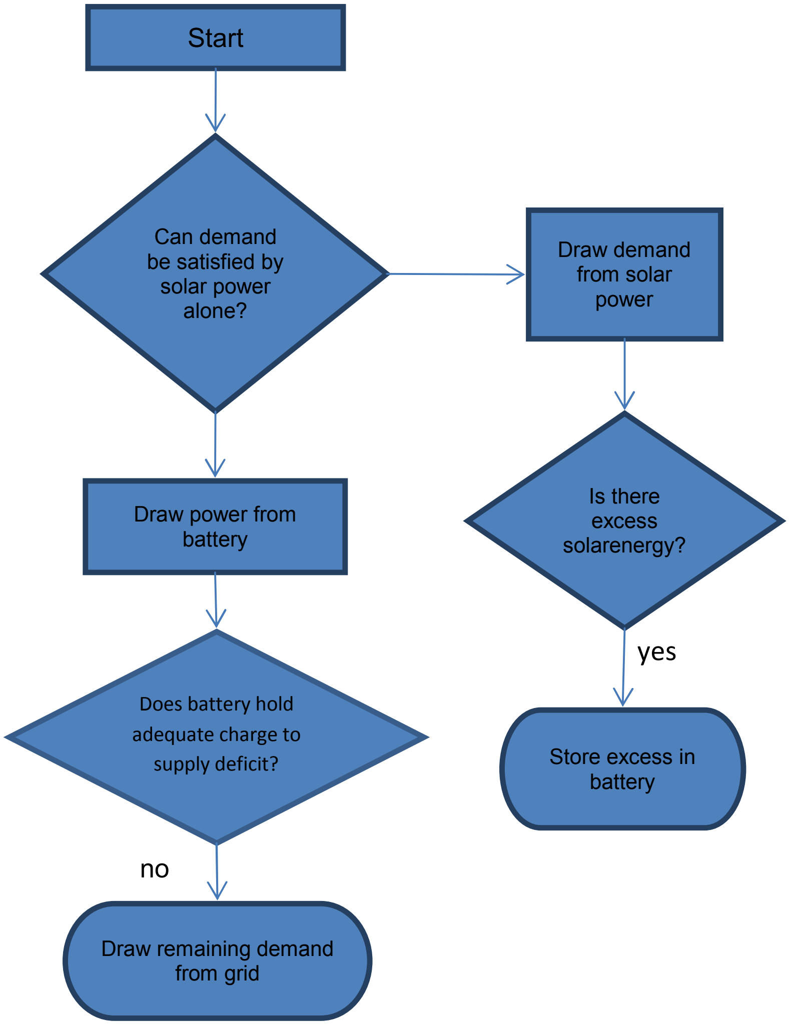

Fig. 2. Flow chart illustrating the function of the energy storage model

3. RESULTS AND DISCUSSION

The above model was implemented in Microsoft Excel and applied based on solar power available during the month of March since this is the most typical month as identified in table 3 above and this relates to the time of year when the energy data was captured. The energy flow during the course of a day is modeled.

3.1Utilisation of Solar Energy without Buffering

Table 4 below shows the amount of energy produced by solar power and how much can be utilised directly.

Table 4. Direct utilisation of renewable energy

Category	Household	Total renewable energy produced (kWh)	Total energy consumed (kWh)	Total renewable energy consumed (kWh)	Renewable utilisation (%)	Category Average
Family	F1	9.28	19.64	6.50	70.05	57.13
	F2	9.28	6.82	3.04	32.72	
	F3	9.28	8.88	3.91	42.13	
	F4	9.28	25.24	7.77	83.77	
	F5	9.28	16.05	5.29	56.97	
Couples	C1	9.28	9.21	3.82	41.19	39.68
	C2	9.28	7.31	4.32	46.55	
	C3	9.28	11.03	4.95	53.31	
	C4	9.28	4.83	1.73	18.61	
	C5	9.28	8.73	3.59	38.72	
Elderly	E1	9.28	6.57	1.58	17.08	42.91
	E2	9.28	12.30	4.43	47.71	
	E3	9.28	17.65	5.23	56.34	
	E4	9.28	12.04	6.47	69.68	
	E5	9.28	4.50	2.20	23.75	

It can be seen that the ‘Family’ category sees the most direct benefit from the use of renewable energy without any energy storage capability. In this category over 40% of the potentially renewable energy is, on average, unusable meaning it must either be transferred back to the grid or wasted. Fig. 3 shows the power flows involved for participants F1.

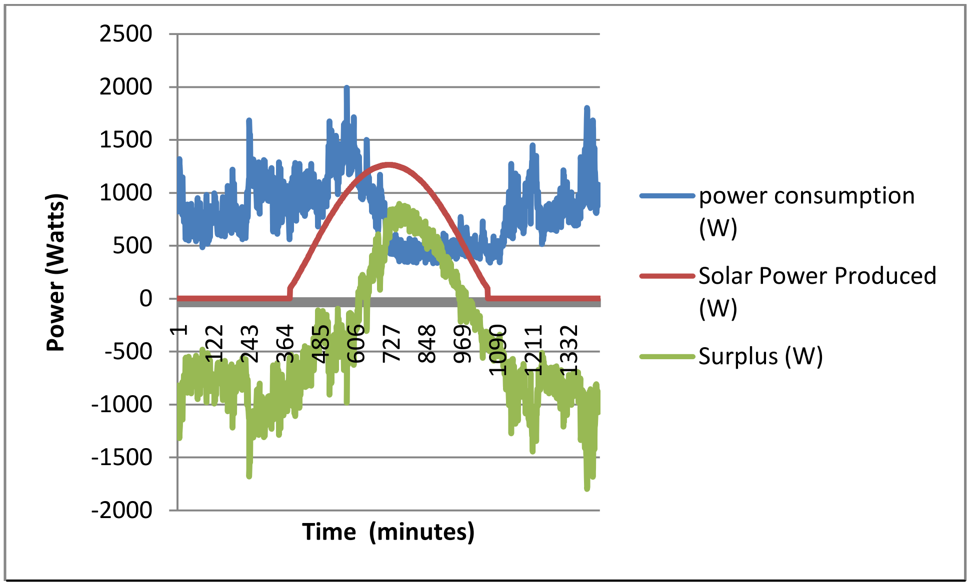

Fig. 3. Power consumption, renewable power production and surplus power through the course of a day

3.2 Utilisation of Solar Energy with Buffering

A buffer pack made up of 10kWh of storage is added to the model as described in equations 2 and 3. Fig. 4 illustrates the power flow for the battery and its state of charge for participant F1. Table 5 shows the degree of utilisation and benefit for the buffer pack in terms of additional reduction in power drawn from the grid. In this instance it is assumed that the battery is empty at the start of each day.

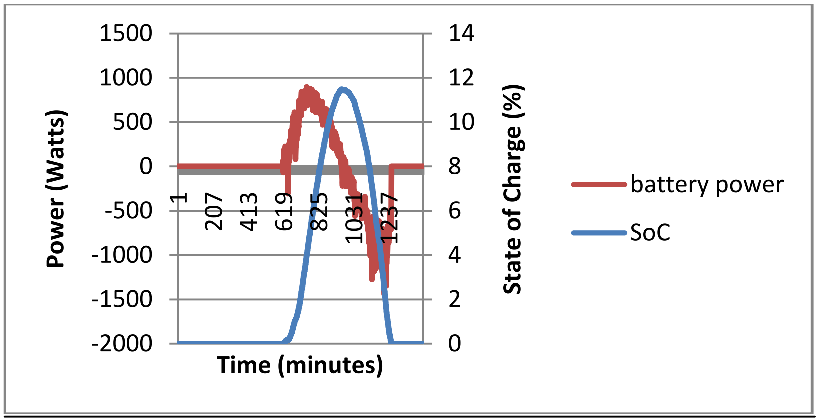

Fig. 4. Battery power and state of charge

Table 5. Utilisation of renewable energy with buffer pack

Category	Household	Total renewable energy consumed (kWh)	Increase renewable energy consumed (kWh)	Max SoC of battery (%)	Additional reduction in grid power (%)	Category average (%)
Family	F1	9.29	2.79	27.57	21.26	45.31
	F2	6.01	2.97	61.82	78.49	
	F3	7.93	4.02	52.04	80.96	
	F4	9.30	1.52	12.66	8.72	
	F5	9.28	4.00	39.29	37.14	
Couples	C1	8.29	4.47	53.70	82.92	76.19
	C2	6.51	2.19	48.19	73.13	
	C3	8.56	3.62	42.80	59.46	
	C4	4.27	2.55	75.12	82.20	
	C5	7.87	4.28	54.46	83.23	
Elderly	E1	4.45	2.87	76.45	57.51	51.59
	E2	8.17	3.74	48.42	47.54	
	E3	9.29	4.06	40.44	32.69	
	E4	8.88	2.42	26.89	43.32	
	E5	3.97	1.77	70.75	76.87	

It can be seen that the addition of the buffer pack has had a notable effect – particularly in the couples category where the grid power required is reduced by 76%. It can also be seen that the degree of utilization of the buffer pack is highly variable between households, indicating that the optimal pack size will vary considerably according to the demand profiles. Table 6 shows the amount of energy provided from renewable sources. It can also be seen from Fig. 4 that the battery charging power does not exceed 1kW and the discharge power does not exceed 1.5 kW. While the specific details of cell configurations, voltages and currents are beyond the scope of this study, for a 10kWh pack it can be seen that the charge and discharge rates which occur are less than 10% and 15% of the 'C' rate respectively. Thus it is unlikely that any accelerated degradation will occur.

Table 6. Percentage of demand supplied by renewable energy with buffer pack

Category	Household	Total energy used (kWh)	Renewable energy consumed (kWh)	% demand supplied by renewables
Family	F1	19.64	9.29	47.32
	F2	6.82	6.01	88.06
	F3	8.88	7.93	89.34
	F4	25.24	9.30	36.83
	F5	16.05	9.28	57.84
Couples	C1	9.21	8.29	90.01
	C2	7.31	6.51	89.01
	C3	11.03	8.56	77.64
	C4	4.83	4.27	88.57
	C5	8.73	7.87	90.13
Elderly	E1	6.57	4.45	67.76
	E2	12.30	8.17	66.42
	E3	17.65	9.29	52.63
	E4	12.04	8.88	73.75
	E5	4.50	3.97	88.19

3.3 Utilisation of Solar Energy with Buffering and Pre Charge

In some instances in the above analysis the battery has charge available at the end of the day, suggesting that the evening energy demand is lower in magnitude than the amount of stored energy. This energy could be used to reduce grid load in the early stages of the subsequent day prior to renewable energy becoming available. In order to investigate this effect a pre-charge of 20% SoC is added to the battery at the start of each day. Table 7 shows the results.

It can be seen that in several cases the entire demand is now supplied by renewable sources. Furthermore, in such cases the final SoC of the battery exceeds the initial value meaning there is adequate power to replace the initial charge prior to the beginning of the next day.

3.4 Financial Analysis of Results

The major incentive for using buffer pack technology will be in increasing the amount of renewable energy which can be used in the home, thus reducing electricity bills. Table 8 shows the cost of power drawn from the grid when no renewable energy is used, when solar power is used without buffering and when solar power is used with buffering. The calculations are based on grid power costing 15 pence per kWh, a value which is consistent with current estimates for UK average prices [25,26].

Table 7. Utilisation of renewable energy with pre-charged buffer pack

Category	Household	Total energy used (kWh)	Renewable energy consumed (kWh)	% demand supplied by renewables	Final SoC of battery (%)
Family	F1	19.64	11.29	57.50	0.00
	F2	6.82	6.82	100.00	44.57
	F3	8.88	8.88	100.00	24.04
	F4	25.24	11.30	44.75	0.00
	F5	16.05	11.28	70.31	0.00
Couples	C1	9.21	9.21	100.00	20.72
	C2	7.31	7.31	100.00	39.71
	C3	11.03	10.56	95.78	7.23
	C4	4.83	4.83	100.00	64.54
	C5	8.73	8.73	100.00	25.50
Elderly	E1	6.57	6.45	98.22	48.33
	E2	12.30	10.17	82.68	11.18
	E3	17.65	11.29	63.96	0.00
	E4	12.04	10.88	90.36	3.98
	E5	4.50	4.50	100.00	67.77

Table 8. Potential cost savings due to renewable energy and buffer packs

Category	Household	Cost of supplying all power from grid (£)	Cost of power from grid when using solar power (£)	Daily saving due to use of solar power (£)	Cost of power from grid when using solar power and buffer (£)	Daily saving due to buffer pack (£)
Family	F1	2.95	1.97	0.97	1.25	0.72
	F2	1.02	0.57	0.46	0.00	0.57
	F3	1.33	0.75	0.59	0.00	0.75
	F4	3.79	2.62	1.17	2.09	0.53
	F5	2.41	1.61	0.79	0.71	0.90
Couples	C1	1.38	0.81	0.57	0.00	0.81
	C2	1.10	0.45	0.65	0.00	0.45
	C3	1.65	0.91	0.74	0.07	0.84
	C4	0.72	0.46	0.26	0.00	0.46
	C5	1.31	0.77	0.54	0.00	0.77
Elderly	E1	0.98	0.75	0.24	0.02	0.73
	E2	1.84	1.18	0.66	0.32	0.86
	E3	2.65	1.86	0.78	0.95	0.91
	E4	1.81	0.84	0.97	0.17	0.66
	E5	0.68	0.34	0.33	0.00	0.34

It can be seen that the use of a buffer pack leads to substantial savings, of the same order of magnitude as the savings due to the use of renewable power alone. Table 9 shows the 10 year savings possible in each category.

Table 9. 10 year savings estimates

Category	Estimated 10 year saving due to using solar power alone (£)	Estimated 10 year saving due to using buffer pack with solar power (£)
Family	2904	2528
Couples	2017	2436
Elderly	2181	2562
Overall:	**2367**	**2509**

It can be seen from Table 9 that the approximate value of £250 per kWh can be deduced from the 10 year savings.

4. CONCLUSION

The analysis carried out has allowed us to draw several conclusions:

- The use of buffer packs has the potential to increase the degree of utilisation of renewable energy sources by matching demand to availability.
- In some cases it is possible that this may lead to the elimination of the need to draw power from the grid. It is noted that this is unlikely to be the case during the winter months when energy demand is expected to rise while renewable power falls.
- Optimal sizing of buffer pack will vary between households due to variations in energy consumption patterns.
- Based on the simulation carried out, the average value of buffer pack storage, in terms of reductions in energy purchased from the grid due to buffering, is estimated to be approximately £250 per kWh. If it assumed that buffer packs are to be comprised of second life EV batteries whose capacity has degraded to 80% of its original capacity, this suggests a potential second life value of £200 per kWh original capacity. The current cost of new EV batteries is approximately \$750/£500 per kWh [27]. This has two potential implications:

    - ❖ It is unlikely that new batteries will be viable for buffer pack applications until the cost of batteries and cells drops considerably.
    - ❖ The potential value of buffer pack storage has potential to improve the value equation for battery electric vehicles by reducing the overall cost of battery replacement. The residual value of second hand EV batteries is currently unknown as few examples exist. This value is likely to be influenced by the value of these cells in the second life applications in which they are used. However the relatively low second life value means it is likely that other second life applications may offer an improved second hand value for the cells. It should be noted that the cost of repackaging the cells for such applications has not been included here in the analysis.

While the study reported herein has allowed us to draw the above conclusions, it is noted that there are inherent limitations in the data used. Based on this, and the conclusions drawn above, the following future work is proposed:

- Collection of energy use data for an entire year to allow the process to be repeated to investigate the effects of seasonal variations in consumption due to changes in the use of lighting, heating etc to be investigated alongside variation in the amount of energy available from renewable sources.
- A detailed investigation of variations in social groups in terms of energy use patterns and the effects on the suitability, benefits and optimal sizing of buffer packs.
- A detailed investigation of the costs involved in remanufacturing and repackaging second life EV cells to support a full analysis of the lifecycle costs involved.
- A full electrical model of the system allowing the rate of charge/discharge to be investigated to allow conclusions to be drawn regarding the implications for cell life and degradation. Furthermore the effect of charge/discharge rate on overall lifecycle cost should be investigated.
- An investigation into the safety implications of operating a battery system whose voltage is likely to exceed the usual voltage of the domestic supply, including the need for adequate isolation and the packaging requirements. It is recommended that the guidelines and standards in place for domestic electric vehicle charging equipment (e.g. those provided by the IET in the UK [28]) should be used a starting point for such a review.

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COMPETING INTERESTS

The authors have no competing interests to declare.

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