Economic and environmental impact of lead-acid batteries in grid-connected domestic PV systems

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6th November 2012

Abstract

Occupants of dwellings with grid-connected photovoltaic (PV) systems can often benefit financially from exporting electricity to the grid. When export prices are lower than import prices, however, occupants are incentivised to time-shift demand in order to avoid exports and reduce imports. To maximise this potential financial benefit, the addition of batteries to the PV system has been proposed to take advantage of the specific commercial opportunity presented to the occupant of trading exported power during the day for imported power during the evening. This paper therefore assesses the economic and environmental impact of the use of lead-acid batteries in grid-connected PV systems under current feed-in tariff arrangements in the UK. The development of a lead-acid battery model is described, which is used to simulate hypothetical power flows using measured data on domestic PV systems in the UK. The simulation results indicate that the net benefit of the battery is negative, even when considering an idealised lossless battery. When realistic energy losses and lifetimes are accounted for, the financial loss for the systems considered here can approach £1000/year. The environmental impact of the use and production of the lead-acid battery is also described, and also found to be negative, further strengthening the argument against the use of lead-acid batteries in domestic grid-connected PV systems.

Keywords: lead-acid battery; PV system; feed-in tariff; environmental impact.

1. Introduction

There is considerable interest in the use of electrical storage technology in low-carbon power systems. At the national transmission system level, large-scale storage could help system balancing with high penetrations of wind power [1]. At the level of the local distribution network, intelligent management of battery charging in electric vehicles could help prolong the use of existing network assets, avoiding unnecessary costs [2]. At the domestic level, the use of batteries in grid-connected photovoltaic (PV) systems has been proposed for the purposes of minimising grid exports [3], improving consumer economics by exploiting retail electricity tariffs with variable pricing [4], and increasing self-consumption with feed-in tariffs [5].

The use of batteries in grid-connected domestic PV systems mentioned in the previous paragraph is investigated in this paper. An economic and environmental impact analysis is presented for the use of lead-acid batteries in PV systems under current feed-in tariff arrangements in the UK, where the specific commercial opportunity for the occupant is in reducing exported power during the day, and trading this for a reduction in imported power during the evening.

The present work builds on previous work by Jenkins [3,6] on the impact and ageing of lead-acid batteries in grid-connected domestic PV systems in the UK. The present work, however, differs considerably from Jenkins' work: the economic impact of the battery for the occupants takes into account current UK feed-in tariff arrangements, recorded data is used from multiple domestic dwellings with PV, a novel battery model is developed, and the environmental impacts of the battery are considered. This work also builds on previous work by one of the authors on the environmental impact of battery production [7], by also considering the in-use environmental impacts of the battery for such applications.

The approach taken in this paper is to develop a model of a lead-acid battery, which is applied to recorded data from UK dwellings with PV systems. The model is used to simulate hypothetical power flows for the PV system with battery. Section 3 describes the development of the battery model, and the method used to calculate the simulated power flows, cost benefits, and environmental impacts associated with the battery. Section 4 then presents and discusses the results of the economic and environmental analysis, with section 5 providing the concluding remarks.

2. Feed-in tariffs and the financial benefits in time-shifting demand

This paper considers domestic grid-connected PV systems on a current UK feed-in tariff, which consists of a generation price (21.0 p/kWh at the time of writing) paid for generated units, and an export price of 3.2 p/kWh paid for exported units [8]. An import price of 11.8 p/kWh has been assumed, which is a typical value for a domestic consumer on a 'standard' flat-rate demand tariff [9].

In this context, occupants with PV systems can benefit financially by using electricity generated by their PV rather than exporting it to the grid [10]. Occupants could typically achieve this by changing their behaviour or routines in order to shift their demand to the middle of the day when their PV is generating [11], for example by eating a hot meal at lunch rather than dinner, or with the help of technology such as timers, that can delay when appliances are switched on.

A further option available to the occupants, considered here, is the use of battery storage [12]. In the UK context, the battery is charged during the day using cheap surplus PV generation, and discharged during the evening and night, to avoid the expensive imports from the grid [3]. Note that battery systems of this type are commercially available for this purpose in the UK [13,14].

3. Method

This section describes a novel method for developing a realistic lead-acid battery model. The battery model is empirical, using existing work as input data – the novelty lies in how this data is combined in order to create a realistic model. The authors note that there are numerous other approaches to modelling lead-acid batteries in PV systems and refer interested readers to [3,15-17].

The model estimates the battery efficiency under varying rates of charge and discharge, as well as varying states of charge. Operational energy losses are quantified using the concepts of voltage efficiency and coulombic, or charge, efficiency. The overall energy efficiency of the battery can be viewed as the product of the battery's voltage and coulombic efficiencies.

The voltage efficiency reflects the fact that charge is removed from a battery at low voltage, while charge is added to it at a higher voltage. This difference in charging and discharging voltage inevitably results in energy losses.

Coulombic efficiency reflects the fact that more charge has to be put into the battery than it is possible to subsequently remove. Coulombic efficiency, in particular, is adversely affected by rapid charging and rapid discharging. Due to the 'peaky' nature of domestic dwelling demand [18], losses associated with rapid discharging will be particularly significant for the application considered in this paper. Finally, both voltage and coulombic efficiency are also reduced at high states of charge [19].

The model is based on the data sheet of a BP Solar 'PVstor' valve-regulated lead-acid battery [20], which is designed for use in stand-alone PV systems. While these batteries may not be optimised for grid-connected systems, nonetheless it is assumed that batteries for these two applications will have broadly similar characteristics. Three battery sizes from the PVStor range are considered, detailed in Table 1. A 48 V battery system has been chosen, as this is the voltage level specified for the chosen inverter (described in section 3.7).

Table 1 – Details of the batteries used in the study.

	Battery option 1	Battery option 2	Battery option 3
Capacity	210 Ah	430 Ah	570 Ah
Voltage	48 V	48 V	48 V
Energy capacity	10.08 kWh	20.64 kWh	27.36 kWh
Estimated battery cost	£1280	£2621	£3475
Inverter size	2.02 kW	4.13 kW	5.47 kW
Estimated inverter cost	£1222	£2502	£3316

3.1. Battery charge and discharge voltage

Figure 1A has been adapted from the manufacturer's data sheet and shows battery cell voltage as a function of state of charge for varying rates of charge and discharge. The top four lines represent the charge voltages, while the bottom four represent discharge voltages. The different currents are indicated by 'C' values. C100 refers to a constant current that would fully discharge the battery over a period of 100 hours. For a 430 Ah battery, C100 is equal to 4.3 A, and C10 is equal to 43 A. For a 210 Ah battery, C100 is 2.1 A, and so on. C values have the same magnitude for both charging and discharging. The general relationship is as follows:

$$C_n = \frac{C_{nominal}}{n}$$

Equation 1

Where:

n – discharge time (hours).

C_n – 'C' value for a discharge time n (A).

$C_{nominal}$ – nominal capacity of the battery.

3.2. Voltage efficiency

It can be seen from Figure 1A that, for a given state of charge, the rate of discharge has less effect on the voltage compared to the rate of charge. As a result, in the model, the voltage efficiency is applied to the charge phase and not the discharge phase. The model therefore estimates the voltage efficiency as a function of the state of charge and rate of charge. Figure 1B shows the voltage efficiency which is estimated here as the ratio of the discharge voltage over the charge voltage, taken at the same rate of charge and discharge. As expected, efficiencies tend to be lower at high state of charge, and high currents.

3.3. Coulombic efficiency

The effect of state of charge on coulombic efficiency is estimated from Stevens [19], which gives empirical data for coulombic efficiency at different states of charge for a valve regulated lead-acid battery used in PV applications. Coulombic efficiency is defined here as amp-hours output over amp-hours input. This data is reproduced in Figure 2A, and shows the reduction in coulombic efficiency associated with incremental changes in battery state of charge. Stevens only gives data for states of charge above 70%, though this is sufficient for this battery model because a minimum state of charge of 60% is used.

Figure 2A shows that, while coulombic efficiency is high for states of charge below 70%, it decreases considerably as the battery reaches a fully charged state. Intuitively, this reflects the fact that, as the battery is charged, it becomes increasingly difficult to charge it further. Note that Stevens' experiment only tested a single rate of charge and discharge, in this case a value close to the battery's nominal discharge rate. In the model, as a matter of choice, the coulombic efficiency as a function of state of charge is applied to the battery charging cycle, though it could equally have been applied on the discharge cycle.

The effect of the rate of discharge is considered independently. This is estimated from data from the manufacturer describing the available battery capacity (in Ah) as a function of varying rates of discharge [20]. Table 2 reproduces the data for the 430 Ah battery. This shows that the capacity available is decreased if the battery is discharged at higher currents. A second, independent coulombic efficiency is therefore estimated as the ratio of the capacity available at a given discharge rate compared to the capacity available at nominal discharge rate (C100). This is shown as a function of discharge current in Figure 2B for the three battery sizes considered here. In the model, this coulombic efficiency is applied to the discharge phase. When modelled in this way, the round trip efficiency for a full charge followed by a full discharge at C100 is approximately 73%. For C10, the round trip efficiency is 44%. Note that these round-trip efficiencies are for illustration only - the operation of the battery in the model does not use full discharge cycles.

Table 2 – Discharge characteristics of the 430 Ah battery at varying rates of discharge at 25 ^{o}C.

	Hours for full discharge	Discharge current (A)	Capacity available (Ah)	Coulombic efficiency
$C_{0.5}$	0.5	194.00	97	23%
C_{1}	1	110.00	110	26%
C_{2}	2	64.00	128	30%
C_{3}	3	50.67	152	35%
C_{4}	4	39.50	158	37%
C_{5}	5	33.20	166	39%
C_{6}	6	29.83	179	42%
C_{7}	7	27.29	191	44%
C_{8}	8	27.13	217	50%
C_{9}	9	26.11	235	55%
C_{10}	10	25.50	255	59%
C_{25}	25	12.32	308	72%
C_{50}	50	7.22	361	84%
C_{100}	100	4.30	430	100%

3.4. Calculation of power flows

The battery efficiencies described above are then applied to the system shown in Figure 3. This presents a one-line diagram showing the major electrical components of the PV system with battery storage that is modelled in this paper. A description of the variables used is provided in Table 3. The PV system shown here is fully metered, as it includes an export meter as well as a generation meter.

Table 3 – Description of variables.

Variable	Description
P_{pv}	PV generation (kW).
P_e	PV output exported to grid (kW).
P_i	Electricity demand imported from the grid (kW).
$P_{net} = P_e - P_i$	Dwelling's net power flow (kW).
$P_d = P_{pv} - P_{net}$	Consumer electricity demand (kW).
P_{bat}	Power from battery (kW).
I_{bat}	Current from battery (A).
V_{bat}	Battery voltage (V).
SOC	Battery state of charge (%).
η_{inv}	Battery inverter efficiency.
$\eta_{voltage}$	Battery voltage efficiency.
η_{SOC}	Battery coulombic efficiency due to state of charge.
$\eta_{dischage}$	Battery coulombic efficiency due to rate of discharge.
t	Time (hours).

Note that the battery is connected via a DC-AC converter to the consumer unit (distribution board), and not connected via DC to the PV, as for example is proposed by Braun et al. [5]. This is for practical considerations, as the PV and battery have different DC voltages and separate converters are more likely to be 'off the shelf' components, as well as to avoid losses in the battery before the units generated by the PV are metered by the generation meter. Note that a technical comparison of different system configurations is out of scope of this paper.

Battery power flows are then calculated as follows. The battery is charged when the following conditions are met:

$$P_{pv} > P_d \text{ and } SOC < SOC_{max}$$

The battery is disconnected when either the minimum state of charge SOC_{min} (60%) or maximum state of charge SOC_{max} (100%) is reached. This constraint has been imposed in order to ensure maximum battery life as per the manufacturer's recommendations [20].

The battery charging current is then calculated as:

$$I_{bat} = \frac{\eta_{inv}(P_d - P_{pv})}{V_{bat}}$$

Equation 2

Charging current is limited to C13 (33 A for a 430 Ah battery), based on battery manufacturer's recommendations [20].

The charge entering the battery (Q_{charge}) is then calculated by:

$$Q_{charge} = -\eta_{voltage}\eta_{SOC}I_{bat}t$$

Equation 3

The minus sign is necessary because charging currents are taken as negative in the model.

State of charge in time interval i is then:

$$SOC(i) = SOC(i-1) + Q_{charge}(i)$$

Equation 4

The battery is discharged when the following conditions are met:

$$P_{pv} < P_d \text{ and } SOC > SOC_{min}$$

In which case the battery discharge current is given by:

$$I_{bat} = \frac{P_{bat}}{\eta_{inv} V_{bat}}$$

Equation 5

Discharge current is limited to C5 (86 A for a 430 Ah battery), again based on manufacturer's recommendations. The charge leaving the battery ($Q_{discharge}$) is then given by:

$$Q_{discharge} = \frac{I_{bat} t}{\eta_{discharge}}$$

Equation 6

State of charge in time interval *i* is given by:

$$SOC(i) = SOC(i-1) - Q_{discharge}(i)$$

Equation 7

3.5. Calculation of economic benefit of battery operation

The operation of the battery will reduce exports and imports. The reduction in exports is an opportunity cost to the system owner, while the reduction in imports is a benefit due to avoided costs. The economic benefit associated with the battery in time interval *i*, $m_{net}(i)$, is calculated by:

$$m_{net}(i) = \Delta m(i) - \Delta c(i)$$

Equation 8

Where $\Delta m(i)$ is the change in income to the occupant in time interval *i* associated with the battery. This is the difference between the income to the occupant associated with generation and export payments with the battery and the equivalent income without the battery. For example, if the battery reduced exports in time interval *i*, then $\Delta m(i)$ would be negative.

$\Delta c(i)$ is the change in costs to the occupant in time interval *i* associated with the battery. This is the difference between the cost of electricity consumed within the dwelling with the battery compared to the equivalent cost of electricity without the battery. For example, if the battery reduced imports in time interval *i*, then $\Delta c(i)$ would be negative, as costs would be reduced.

The estimate of the total economic benefit of the battery (not including equipment costs) is then given by the sum of m_{net} over the course of a whole year for the dwellings described in the following section.

3.6. Description of data used in the analysis

In Figure 3, power flows denoted with an asterisk indicate where recorded data on domestic dwellings with installed PV in the UK has been used from the Photovoltaic Domestic Field Trial ("DFT") [21]. The battery model is used to simulate hypothetical power flows given the addition of a battery to the systems. In the model, the dwelling demands and PV generation are unchanged from those of the DFT systems. The resolution of the data is 5 minutes.

The study uses data from two of the Domestic Field Trail's sites. The first site consists of data from 22 dwellings, and the second site consists of data from 15 dwellings. Annual irradiances for the two sites were 894.7 kWh/m^2, and 892.8 kWh/m^2, which are quite typical for the UK [22].

Note that the sizes of PV systems installed in the dwellings considered here range between 1.5 kW_{peak} and 3.29 kW_{peak}, while recent installations in the UK are closer to 4 kW_{peak}. The applicability of the results to more modern systems will be discussed in the results.

3.7. Battery inverter

The battery inverter is based on the SMA Sunny Backup 5000 [13], which includes battery charge regulator and power electronic converter. The efficiency of the inverter is modelled on the efficiency curve provided in this product's manual. The inverter has a peak efficiency of 95.4% and efficiency of more than 91% throughout most of its operating range. Note that this efficiency applies to charging as well as discharging. The inverters are sized for the maximum discharge current of the batteries multiplied by the battery voltage, giving the inverter sizes shown in Table 1.

3.8. Cost and lifetime of equipment

Costs were estimated as the cost of the equipment (battery and battery inverter) divided by its expected lifetime. Battery costs have been estimated at $200/kWh from a Sandia National Laboratories Report [23]. The cost of the battery inverter has been estimated at £606/kW, based on lowest of three quotes for 'SMA Sunny Backup systems' produced from an internet search [24-26]. The Sunny Backup has been chosen as it is a battery inverter that is currently commercially available and designed for the purposes in hand. Table 1 shows the inverter sizes for the three batteries considered here.

Inverter lifetime was assumed to be 10 years. Battery lifetime is estimated from Jenkins' design equation, which estimates the useful lifetime for lead-acid batteries in grid-connected residential PV systems as a function of the battery size and usage [6], as follows:

$$T = \frac{329.9 \times S}{E_e}$$

Equation 9

Where:

T – estimated battery lifetime (years).

E_e – Annual exports available from the PV system (kWh/year).

S – battery capacity (kWh).

3.9. Environmental impact

The environmental impact is considered in two areas: production impacts, and in-use impacts. For both of these, the analysis compares the impact associated with adding a battery to the PV systems considered here, compared to the same PV systems without battery.

3.9.1. Production impacts

The production impact of lead acid batteries was determined by examining the processes and materials contained within the battery. While a full Life Cycle Assessment was not undertaken, a life cycle approach was taken, following the ISO Standards [27,28]. This was done using SimaPro software, and was originally described by McManus [7]. Three environmental issues have been assessed; the impact on greenhouse gases (GHG), fossil fuel depletion, and metal depletion. These were analysed using both IPCC data and the 'Recipe' LCA methodology [29]. The work has focused on these three areas as previous research has shown these are some of the major impact areas for battery use and production [7]. In addition, GHG and fossil fuel depletion are major policy drivers within the energy arena, and the impact of metal depletion has been widely discussed as a potential area for concern associated with the use and production of batteries [30].

The production impacts of lead-acid batteries per kg of battery weight in terms of greenhouse gases, metal depletion, and fossil fuel depletion are 0.9 kg CO_{2eq}, 0.4 kg Fe_{eq}, and 0.3 kg oil_{eq} respectively [7]. The contribution to greenhouse gases and fossil fuel is predominantly associated with the extraction and processing of lead and the polypropylene used in the battery production. The contribution to metal depletion is dominated by the lead within the battery. Note that this approach assumes a mix of virgin and recycled materials is used in the battery production, based current norms, as described by McManus [7].

3.9.2. In-use impacts

The in-use impact of the batteries is associated with the time-varying environmental impact of grid-electricity [31]. From the perspective of the national grid, the effect of adding a battery to a PV system (where previously there was none) is to increase demand during the day, when the battery is charging, and to decrease demand during the evening, when the battery is discharging. These changes in demand throughout the course of the day will result in corresponding changes in generation from fossil fuel plant. Moreover, due to losses in the battery it can be expected that the increase in daytime generation will be greater than the corresponding decrease in generation during the evening, meaning that the battery will cause a net increase in fossil fuel generation, with a resulting negative environmental impact.

To calculate how the changes in demand throughout the day associated with adding the battery to the PV system can be expected to result in changes in generation from fossil fuel plant, data from the UK balancing mechanism reports [32] was used to calculate the 'responsiveness' of gas and coal generation to historic changes in demand for each five-minute period in 2009 to 2011. Responsiveness here refers to the change in generation (in kWh) that is associated with a change in demand of 1 kWh.

For some time periods, a calculated responsiveness was uncharacteristically high or low due to operators switching from one plant type to another. To compensate for this effect, time periods were grouped into 144 sets (one for each hour of the day for each two-month period of the year) and the weighted average responsiveness of each plant type was calculated for each set. The average was weighted by the absolute value of the change in total generation during each time period (Equation 10). The resulting values for the responsiveness of coal and gas plant are provided for reference in the Appendix.

$$\overline{\left(\frac{\Delta P_{gen}}{\Delta P_{total}}\right)_h} = \sum_{i=h_1}^{h_n}\left[\left(\frac{\Delta P_{gen}(i)}{\Delta P_{total}(i)}\right)\left(|\Delta P_{total}(i)| \Big/ \sum_{i=1}^{h_n}|\Delta P_{total}(i)|\right)\right]$$

Equation 10

Where:

$\overline{\left(\frac{\Delta P_{gen}}{\Delta P_{total}}\right)_h}$ - weighted average responsiveness of electricity generated by coal or gas plant to unit changes in total electrical demand during the time periods in set h (h_1 to h_n).

$\Delta P_{gen}(i)$ – increase in average electrical power generation from gas or coal generating plant during period i.

$\Delta P_{total,}(i)$ – increase in average electrical power generation for whole electrical grid during period i.

The net change in generation from coal and gas is then calculated by multiplying the weighted average responsiveness for gas and coal generation for each 5 minute time step by the net change in demand associated with adding the battery to the PV system, and summing these over the entire year (Equation 11). The net change in demand is determined by the battery model described above.

$$\Delta E_{gen} = \sum_{i=1}^{n} \left[\Delta P_{net}(i) t \left(\frac{\Delta P_{gen}(i)}{\Delta P_{total}(i)} \right) \right]$$

Equation 11

Where:

ΔE_{gen} – total net change in electricity generated from a type of generating plant (gas or coal) for periods 1 to n.

$\Delta P_{net}(i)$ – net change in electrical demand in time period i due to battery operation (compared to PV system without battery).

Environmental impacts in the three areas considered for production are then calculated by multiplying the total net changes in fossil fuel generation by the impact data shown in Table 4. These values were calculated using a life cycle approach using SimaPro software based on data from EcoInvent [33].

Table 4 – Environmental impact of coal and gas generation.

	Climate Change (kg CO_{2eq})	**Metal depletion (kg Fe_{eq})**	**Fossil fuel depletion (kg oil_{eq})**
For 1 kWh electricity from gas generation	0.484	1.01×10^{-3}	0.198
For 1 kWh electricity from coal generation	1.08	3.99×10^{-3}	0.291

4. Results and Discussion

4.1. Battery operation for a single system over a single day

The following results demonstrate the operation of the battery over a single day, illustrating the battery's effect on the dwelling's net power flow, along with the resulting battery efficiencies, and the financial benefit to the occupant.

Figure 4A shows the demand profile for a single dwelling with a 3.29 kWp PV system on the 15th June 2006 from the DFT dataset [21]. Note that the high demand between 00:00 and 03:00 is likely due to electric water heating. The net dwelling power flow to the grid is shown in Figure 4B with and without battery. The battery starts the day at minimum state of charge because it was used the previous evening, so the net power flow is unchanged throughout the morning. At around 07:00, the PV generation starts to exceed the dwelling's demand, and the battery starts charging. This reduces the net power flow to zero throughout most of the day. A small amount of power is still exported, however, when the surplus current from the PV exceeds the maximum charge current of the battery. At around 17:00, the dwelling demand exceeds PV generation, and the battery discharges. The net power flow reduces to zero, until approximately 23:00 when the battery reaches its minimum state of charge, and is disconnected.

Battery state of charge and efficiency is shown in Figure 5. The inverter efficiency, not shown here, remains relatively high (~95 %) throughout the day. The battery charging efficiency and discharging efficiency are shown separately in Figure 5B. As the battery state of charge increases during the day the charging efficiency falls from ~80 % to ~50 %. In the evening, the discharge efficiency is determined by the rate of discharge, and drops below 50 % on a number of occasions.

The cost benefit of the battery operation is shown in Figure 6A. There is a negative benefit throughout the middle of the day, associated with the opportunity cost of reducing exports. This is followed by a positive benefit in the evening as imported electricity is avoided. Figure 6B shows the cumulative benefit for the day, indicating that there was a modest benefit at the end of the day of ~10 p. Note this does not consider equipment costs, which are considered in the following section.

4.2. Cost benefit using realistic battery model

The previous figures showed the effect of the battery over a single day for a single dwelling, and this section extends this to include data from multiple systems from the DFT dataset over the course of a whole year. Data for 37 individual dwellings is considered, corresponding to the two Domestic Field Trial sites mentioned in section 3.6.

Figure 7 shows how the realistic battery results in reductions in imports from the grid and reductions in exports to the grid, for the systems and batteries considered here. The reduction in imports are smaller than the reduction in exports, due to losses in the battery. The gradient of the lines that pass through the data points gives an indication of how many units of exported electricity are used to provide one unit of avoided imported electricity. A least squares fit through the data results in gradients of 2.14 (0.0482), 2.29 (0.0575), and 2.83 (0.0698) for the 570 Ah, 430 Ah, and 210 Ah batteries respectively (standard errors in brackets). These gradients can be compared to the ratio of the import price to the export price, 11.8/3.2 = 3.69. Provided the gradient is smaller than the import export price ratio, then the batteries can be expected to produce a benefit in terms of savings on electricity bills.

Figure 8 shows the resulting annual benefits to the occupants of the dwellings considered here, in terms of reduced costs of electricity, for the three sizes of realistic batteries (black markers). The x-axis shows annual exports for the PV system without battery, as the main purpose of the battery is to reduce these exports. The benefits are low – for the larger systems shown here, which are comparable to modern 4 kW_{peak} PV systems, the benefits of a battery might amount to ~£30/year.

The low benefits shown in Figure 8 are due to the battery inefficiencies which are shown in Figure 9A. This shows annual round-trip efficiencies for the different dwellings and battery size configurations. The round-trip efficiency is calculated here as the total energy out of the battery inverter over the total energy into the battery inverter. The mean round trip efficiency values are 39.1 % for the 210 Ah battery, 53.0 % for the 430 Ah battery, and 58.5 % for the 570 Ah battery.

Figure 10 shows annualised equipment costs for the realistic battery (black markers), which can reach ~£1000/year for the larger systems considered here. The costs increase with available exports, which reflects the reduction in battery lifetimes associated with battery wear, shown in Figure 9B. Systems with high exports result in greater battery wear, and shorter lifetimes. For large systems, comparable to modern 4 kW_{peak} PV systems, a 570 Ah battery has an expected lifetime of 5.23 years, dropping to 1.93 years for a 210 Ah battery.

Figure 11 finally shows the resulting annual net benefit associated with the realistic battery (black markers), which illustrates that there is no economic case for the use of lead-acid batteries for the systems and specific purposes considered here.

4.3. Cost benefit for a lossless battery

Figure 9A illustrates that the operating conditions (specifically the charge and discharge current limits) imposed here can result in battery efficiencies that are very low indeed – to the point of being counter-productive for some systems. Alternative operating conditions or strategies could therefore be considered in order to optimise the system and reduce operational losses. In order to show that the cost benefit results shown in Figure 11 are robust, however, and not contingent on assumptions regarding battery efficiencies, equipment lifetimes, or operating strategy, this section considers the cost benefit for a lossless battery and inverter that are both 100% efficient.

In keeping with the assumption of a lossless battery, the battery is also assumed not to experience any wear, and as such there is no effect on costs associated with increasing annual exports (an indication of how much the battery is used). Equipment lifetimes are therefore optimistic: 20 years for the battery, and 10 years for the inverter. This results in annualised costs of £186.2/year, £381.2/year, and £505.3/year for the 210 Ah, 430 Ah, and 570 Ah battery systems respectively. These are illustrated for comparison alongside the realistic battery costs in Figure 10. Note that the minimum state of charge for the lossless battery is kept the same as that for the realistic battery (60%).

The annual benefits for a perfectly efficient battery is shown in Figure 8 (grey markers) alongside the benefits for the realistic battery, for the same dwellings and battery sizes. For the lossless battery, it can be seen that the annual benefit increases along with the available exports. Larger batteries increase the benefit for larger systems with more exports, but have little effect on the smaller systems. The data for benefits shows that a lossless battery can result in bill savings of up to £110/year.

Figure 11 shows the resulting net benefit of the lossless battery (grey markers), again alongside the equivalent net benefits of the realistic battery (black markers). It is clear that the costs are considerably larger than the benefits for all of the systems considered here, even when assuming a lossless battery with optimistic lifetime estimates. The battery results in a net financial loss to the occupant of around £100/year for the smallest lossless battery, increasing to over £400/year for the largest lossless battery considered here. It appears therefore that there is no economic case for the use of lead-acid batteries for the systems and specific commercial opportunity considered here, even for idealised lossless batteries with optimistic lifetimes.

Note that these results ignore the cost of any routine maintenance, the cost of installation, or indeed any discount rates applied to future benefits. If included, these would obviously worsen the business case.

4.4. Environmental impact

The production impacts for the batteries considered in this paper are shown in Table 5. This production impact is spread over the lifetime of the batteries in use, as estimated by Equation 9, and illustrated in Figure 9B.

Table 5 – Battery weights and production impacts.

				Production impacts		
Battery Capacity (Ah)	**Weight per cell (kg)**	**Number of cells in battery**	**Total battery weight (kg)**	**Climate Change (kg CO_{2eq})**	**Metal depletion (kg Fe_{eq})**	**Fossil fuel depletion (kg oil_{eq})**
210	38	8	304	273.6	121.6	91.2
420	29	24	696	626.4	278.4	208.8
570	37	24	888	799.2	355.2	266.4

Regarding the in-use impacts, the resulting change in fossil fuel generation over the course of the day associated with the operation of a realistic 430 Ah battery is shown in Figure 12. The values for the change in fossil fuel generation are averages for all of the dwellings considered here over the course of the whole year. It can be seen that the battery operation results in an increase in fossil fuel generation during the day, and a decrease in the evening and night. It can be seen that the area above zero is considerably greater than the area below zero, which can be attributed to energy losses in the battery. It is interesting to note that these results show that coal plant is more responsive to changes in demand than gas plant.

The combined annual production and in-use impacts are now considered. Table 6 shows the combined impacts associated with adding a 430 Ah battery to a 3.29 kW_{peak} PV system. These results are comparable to the case of adding a battery to a modern 4 kW_{peak} PV system. Not unexpectedly, metal depletion impact is dominated by battery production, while climate change and fossil fuel depletion impacts are dominated by battery use.

Table 6 – annual production and in-use impacts for 430 Ah battery with 3.29 kW_{peak} PV system. Standard deviations shown in brackets.

	Climate Change (kg CO_{2eq}/year)	Metal depletion (kg Fe_{eq}/year)	Fossil fuel depletion (kg oil_{eq}/year)
Production impacts	127.5 (26.2)	56.6 (11.6)	42.5 (8.7)
In-use impacts	657.7 (137.3)	2.2 (0.5)	201.7 (41.9)
Total	785.1	58.8	244.2
In-use impacts (lossless battery)	5.09 (2.35)	0.0255 (0.0188)	0.79 (0.36)

The mean in-use impact values for the lossless 430 Ah battery are shown for comparison in Table 6. As there are no energy losses with this battery, these values can be interpreted as the impacts associated with the lossless time-shifting of demand from the evening to the day. The difference between the in-use impacts for the lossless battery and those for the realistic battery can therefore be interpreted as the environmental impacts due to energy losses in the battery, which are two orders of magnitude greater than those associated with shifting demand from the evening to the day.

To put these results into perspective, the total annual climate change impact for this battery has an equivalent impact in terms of kg CO_{2eq}/year as driving 4362 km in a 'good' (180 g CO_{2eq}/km) UK petrol vehicle [33]. Alternatively, using the same assumptions regarding responsiveness of fossil fuel plant as detailed in section 3.9.2, it can also be equated to an average 2009 UK household (4460 kWh/year) increasing annual electricity consumption by 946 kWh, an increase of 21%.

4.5. Target capital costs

The theoretical maximum benefit to the occupants considered here is 11.8 p/kWh – 3.2 p/kWh = 8.6 p per kWh of otherwise exported electricity. The mean annual exports for the 37 systems considered here was 605 kWh/year, which gives a theoretical maximum benefit of £52 per dwelling per year. Assuming a modest discount factor of 4% over 20 years, this results in a target up-front capital cost of £707 for the battery system to break even. To put this into perspective, note that the cheapest battery system considered here (210 Ah with optimistic lifetimes) has an equivalent up-front capital cost of £3296.

4.6. Comparison with feed-in tariffs from other countries

The present study has considered the use of batteries with UK feed-in tariffs, where the price differential between export price and import price is 8.6 p/kWh as mentioned above. The results are, however, relevant more generally to other countries with feed-in tariffs that have lower export prices than typical import prices.

In Germany, for example, a typical domestic system installed in 2011 will have an export price of ~29 c€/kWh and a 'self-consumption payment' of ~17 c€/kWh for electricity produced by the PV and consumed within the dwelling [34]. The result is an 'effective export price' of 29 c€/kWh – 17 c€/kWh = 12 c€/kWh, which is 8 c€/kWh cheaper than a typical import price of 20 c/kWh. This results in an import export price ratio of 20/12 = 1.67. As described in section 4.2, the minimum ratio needed to result in a benefit is 2.14 (for the 570 Ah battery). Considering that Germany has a solar resource that is not dissimilar to that of the UK [22], it would appear that the present study's conclusions concerning the lack of business case for batteries in grid-connected PV systems is also applicable to Germany.

The findings are also relevant to PV systems installed from late 2012 in the Australian states of Queensland [35], Victoria [36], and Western Australia [37]. These states have feed-in tariffs with export prices of ~8 cAUD/kWh, which is 17 cAUD/kWh (≈ 10.93 p/kWh) less than a typical import price of 25 cAUD/kWh. The import export price ratio is therefore 3.13, which is again lower than the UK price ratio (3.69). The results of this paper are therefore also applicable to Australian PV systems installed from late 2012 onwards.

Finally, note that this paper has only considered the economic benefit to the occupant associated with the use of the battery given current feed-in tariff arrangements. It is quite possible however that there are additional economic benefits associated with this type of distributed storage, in particular to other stakeholders e.g. system operator, distribution network operator. Quantifying these additional benefits has been left for future research work to consider.

5. Conclusions

The addition of batteries to grid-connected domestic PV systems has been examined for its ability to maximise the financial return of the system. The purpose of the battery is to charge during the day using cheap surplus PV generation, and to discharge during the evening to avoid expensive imports from the grid. This paper has investigated the economic and environmental impact of the use of lead-acid batteries in domestic PV systems under current UK feed-in tariff arrangements.

The results indicate that there is no economic case for the use of lead-acid batteries for the systems considered here, even for idealised lossless batteries with optimistic lifetimes. The realistic battery model developed here produced mean round trip efficiencies of 39.1 %, 53.0 %, and 58.5 % for 210 Ah, 430 Ah, and 570 Ah lead-acid batteries respectively. Unsurprisingly, when these efficiencies and realistic lifetimes are accounted for, the financial losses are considerably worse. For the batteries considered here, losses approaching £1000/year can be expected for a 570 Ah added to a 3.29 kW_{peak} PV system.

The environmental impact of the production and use of lead-acid batteries for this purpose is also negative, and comparable to driving over 4000 km per year in a 'good' UK average petrol car. This further strengthens the argument against the use of such batteries for these purposes.

6. Acknowledgements

This work was supported by the Engineering and Physical Sciences Research Council, UK, within the HiDEF Supergen project (EP/G031681/1). The principal author was also supported by Secure Meters (UK) Ltd. The authors would also like to express their gratitude to the reviewers of this paper for their helpful feedback.

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8. Appendix

Table 7 - Weighted average change in electricity generated by coal to unit changes in total electrical demand in GB electricity market (data from 2009 to 2011).

Hour of day	Period of year					
	0	1	2	3	4	5
0	0.494551	0.455457	0.437542	0.393212	0.396758	0.478689
1	0.496866	0.469524	0.422298	0.368692	0.399714	0.510903
2	0.500799	0.464754	0.440178	0.385595	0.398715	0.50572
3	0.5489	0.432157	0.36836	0.363328	0.379169	0.514606
4	0.566476	0.474136	0.452927	0.398794	0.502077	0.475355
5	0.567946	0.555243	0.506174	0.460635	0.586774	0.559716
6	0.52664	0.61185	0.618944	0.569299	0.627499	0.574908
7	0.562577	0.617038	0.579624	0.585671	0.580824	0.606942
8	0.54072	0.586075	0.558954	0.557762	0.613838	0.544663
9	0.54419	0.550934	0.515535	0.533581	0.532024	0.556299
10	0.527202	0.490187	0.522915	0.53868	0.542271	0.522832
11	0.484315	0.562545	0.556201	0.550072	0.541937	0.53242
12	0.491218	0.598059	0.557904	0.556898	0.547817	0.499456
13	0.496241	0.604643	0.587941	0.534845	0.570576	0.512185
14	0.527025	0.59763	0.582466	0.550426	0.587472	0.512683
15	0.466498	0.604244	0.556948	0.531664	0.564756	0.505471
16	0.509246	0.580713	0.590093	0.573185	0.59181	0.540284
17	0.537683	0.611151	0.6338	0.607297	0.608505	0.51186
18	0.53161	0.630377	0.637861	0.602651	0.62768	0.54301
19	0.544557	0.57606	0.58905	0.586922	0.662873	0.477636
20	0.543458	0.637469	0.565202	0.567295	0.638235	0.51867
21	0.494102	0.650307	0.600947	0.592812	0.636466	0.560413
22	0.518938	0.579318	0.482388	0.492356	0.537305	0.601915
23	0.51428	0.481071	0.452315	0.390059	0.452874	0.556961

Table 8 - Weighted average response in electricity generated by gas (CCGT) to unit changes in total electrical demand in GB electricity market (data from 2009 to 2011).

Hour of day	Period of year					
	0	1	2	3	4	5
0	0.505449	0.544543	0.562458	0.606788	0.603242	0.521311
1	0.503134	0.530476	0.577702	0.631308	0.600286	0.489097
2	0.499201	0.535246	0.559822	0.614405	0.601285	0.49428
3	0.4511	0.567843	0.63164	0.636672	0.620831	0.485394
4	0.433524	0.525864	0.547073	0.601206	0.497923	0.524645
5	0.432054	0.444757	0.493826	0.539365	0.413226	0.440284
6	0.47336	0.38815	0.381056	0.430701	0.372501	0.425092
7	0.437423	0.382962	0.420376	0.414329	0.419176	0.393058
8	0.45928	0.413925	0.441046	0.442238	0.386162	0.455337
9	0.45581	0.449066	0.484465	0.466419	0.467976	0.443701
10	0.472798	0.509813	0.477085	0.46132	0.457729	0.477168
11	0.515685	0.437455	0.443799	0.449928	0.458063	0.46758
12	0.508782	0.401941	0.442096	0.443102	0.452183	0.500544
13	0.503759	0.395357	0.412059	0.465155	0.429424	0.487815
14	0.472975	0.40237	0.417534	0.449574	0.412528	0.487317
15	0.533502	0.395756	0.443052	0.468336	0.435244	0.494529
16	0.490754	0.419287	0.409907	0.426815	0.40819	0.459716
17	0.462317	0.388849	0.3662	0.392703	0.391495	0.48814
18	0.46839	0.369623	0.362139	0.397349	0.37232	0.45699
19	0.455443	0.42394	0.41095	0.413078	0.337127	0.522364
20	0.456542	0.362531	0.434798	0.432705	0.361765	0.48133
21	0.505898	0.349693	0.399053	0.407188	0.363534	0.439587
22	0.481062	0.420682	0.517612	0.507644	0.462695	0.398085
23	0.48572	0.518929	0.547685	0.609941	0.547126	0.443039

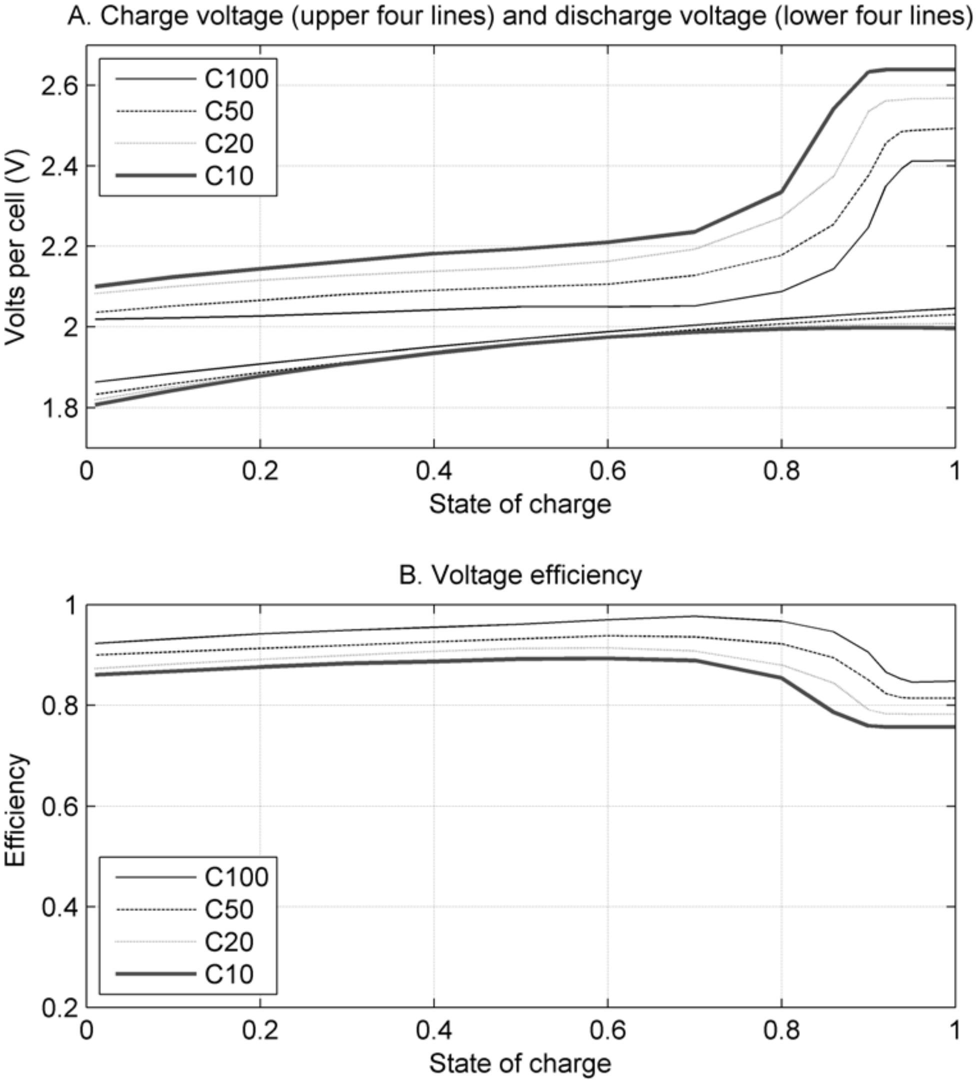

Figure 1 – Voltage efficiency used in the battery model.

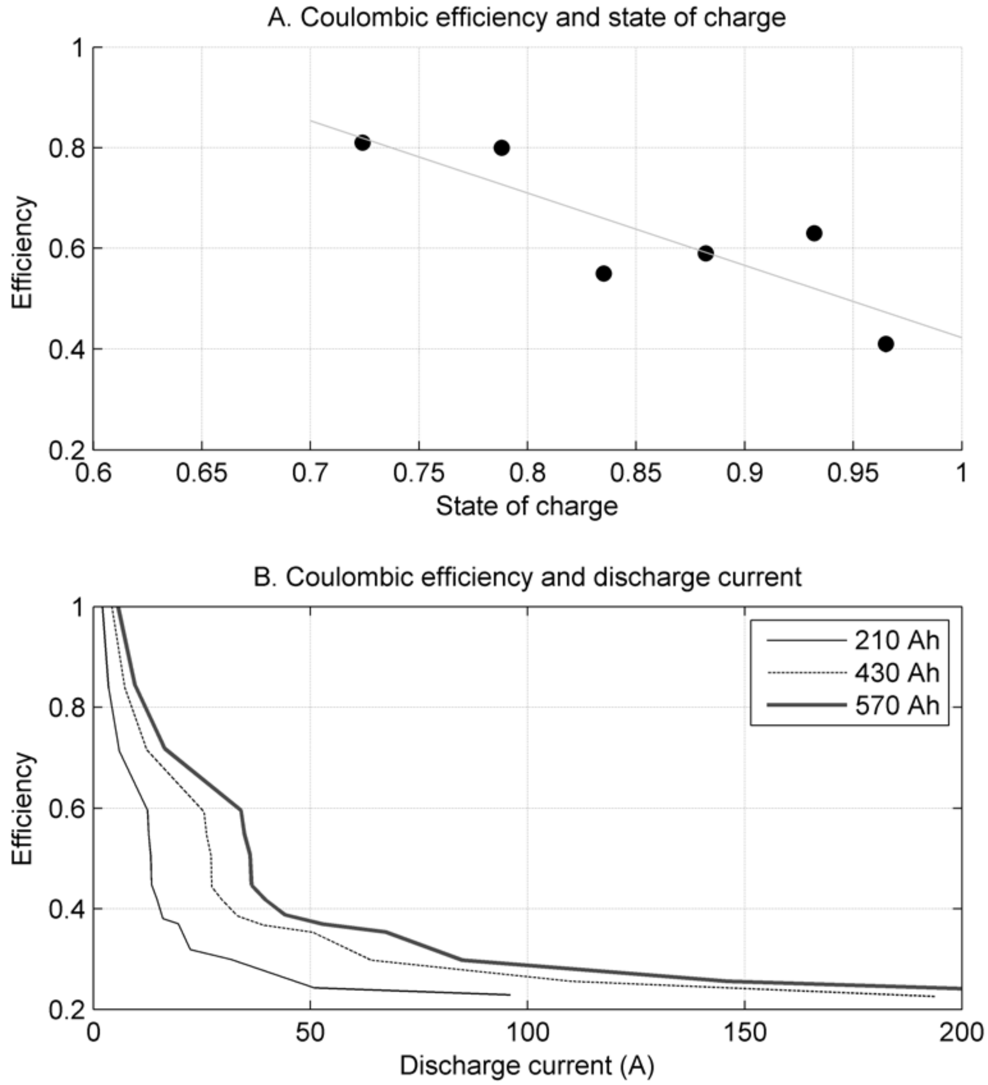

Figure 2 – Coulombic efficiency used in the battery model.

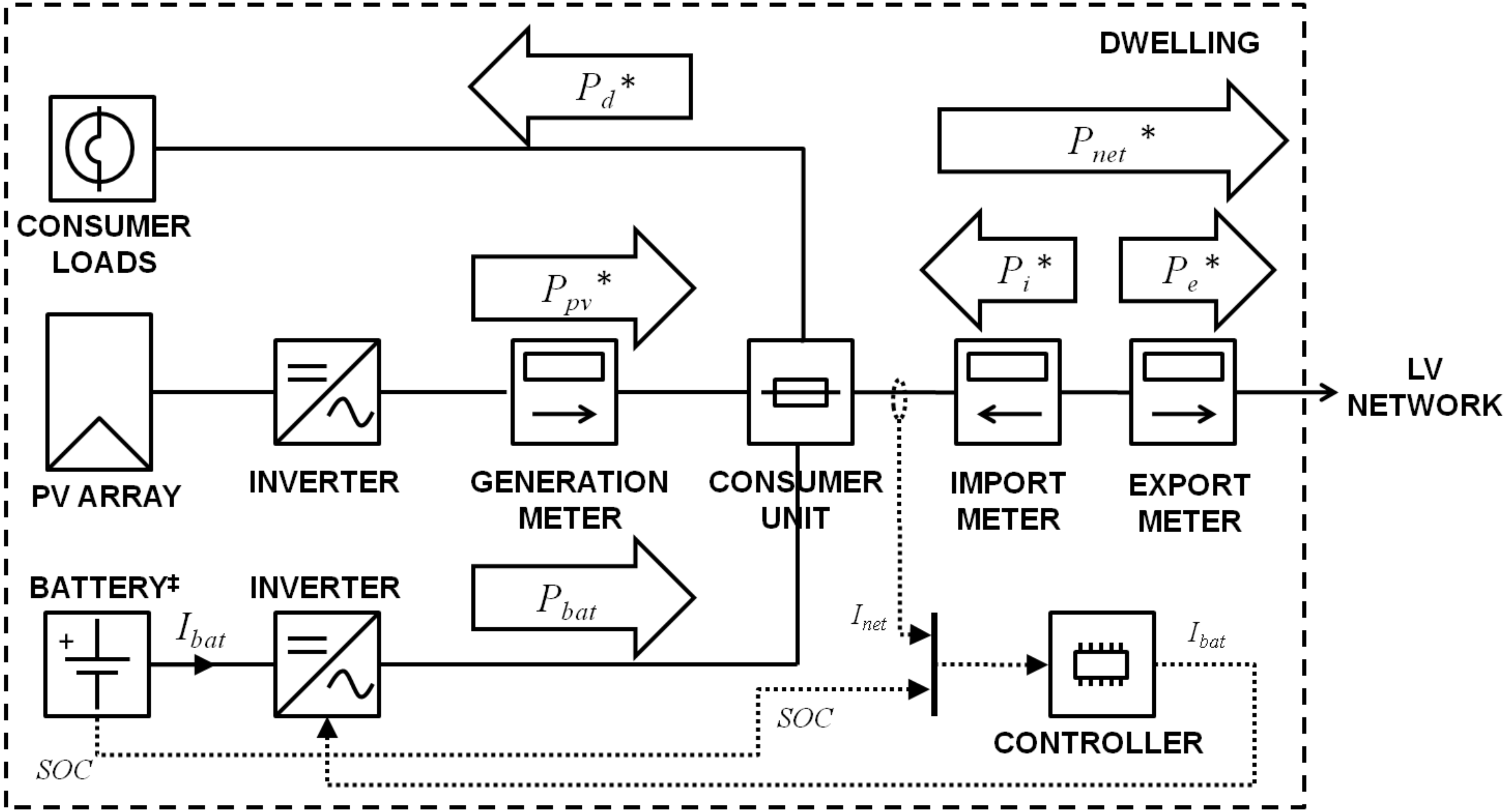

Figure 3 – One-line diagram of a fully metered PV system with battery storage.

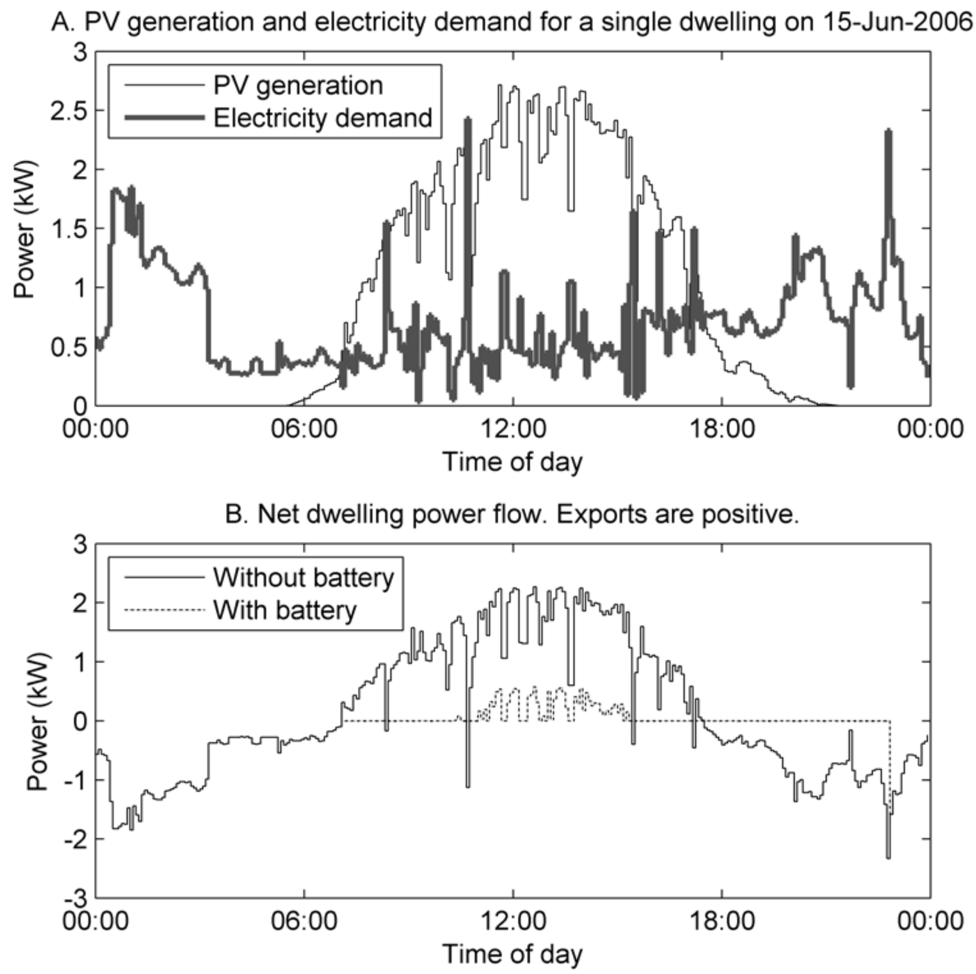

Figure 4 – PV generation, dwelling demand, net power flow to the grid, before and after battery.

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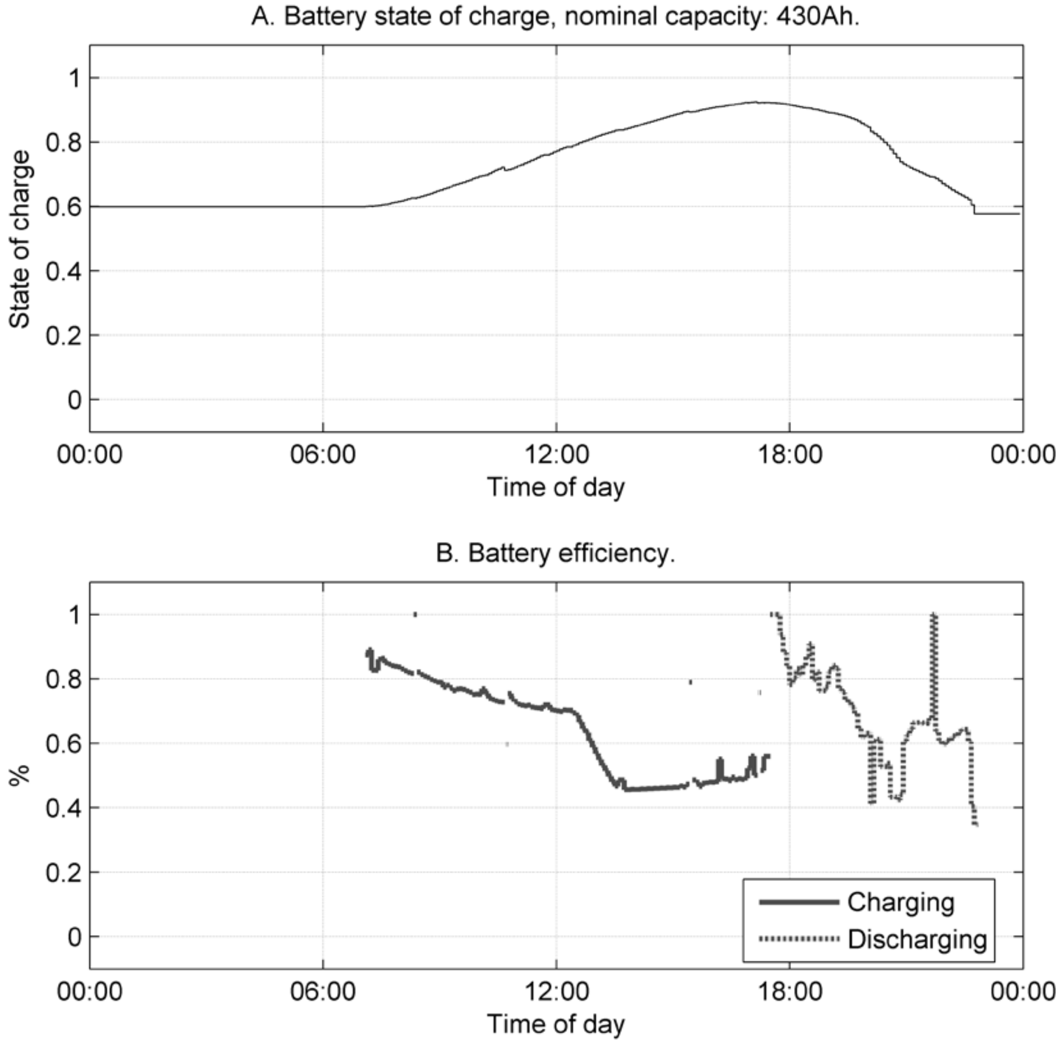


697 **Figure 5 – Battery state of charge and efficiency.**

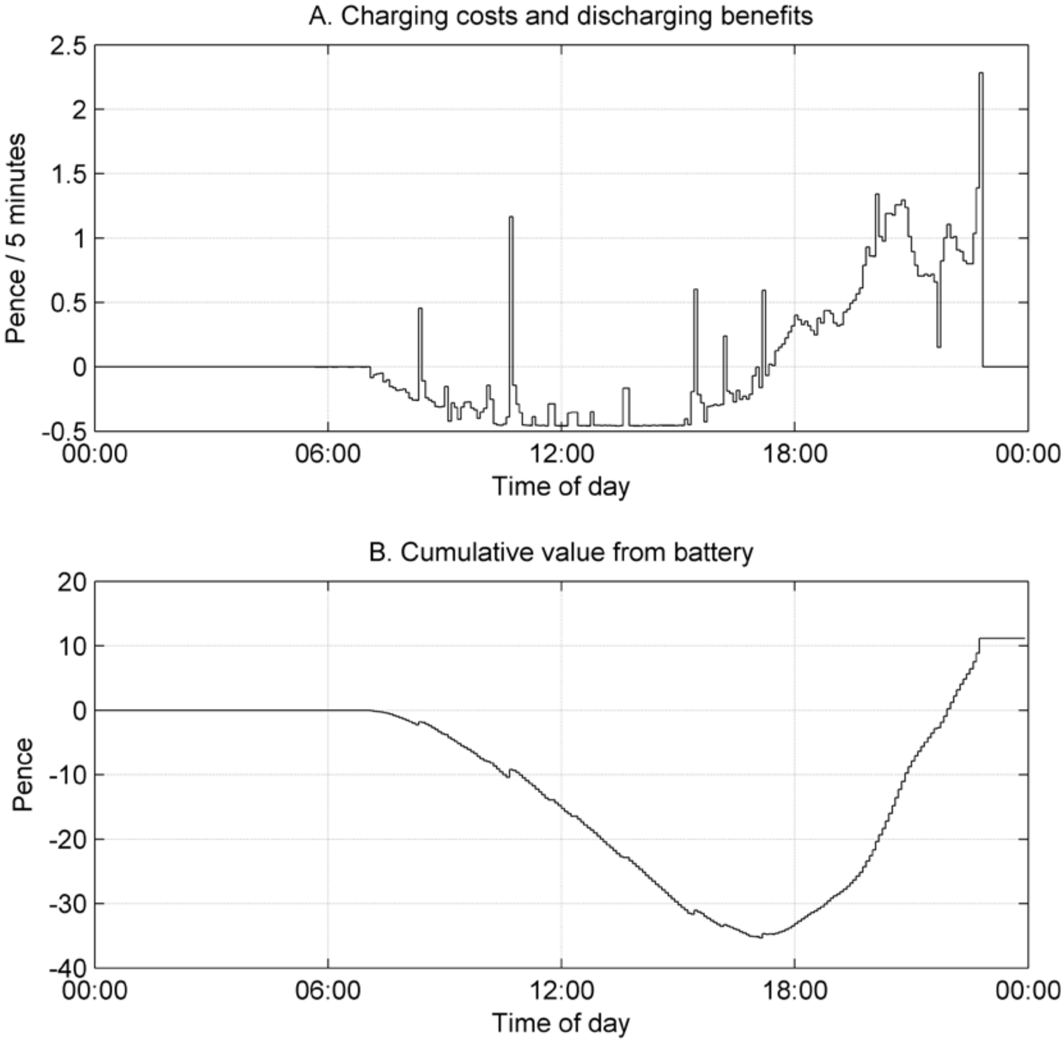


Figure 6 – Cost benefit over the course of a single day.

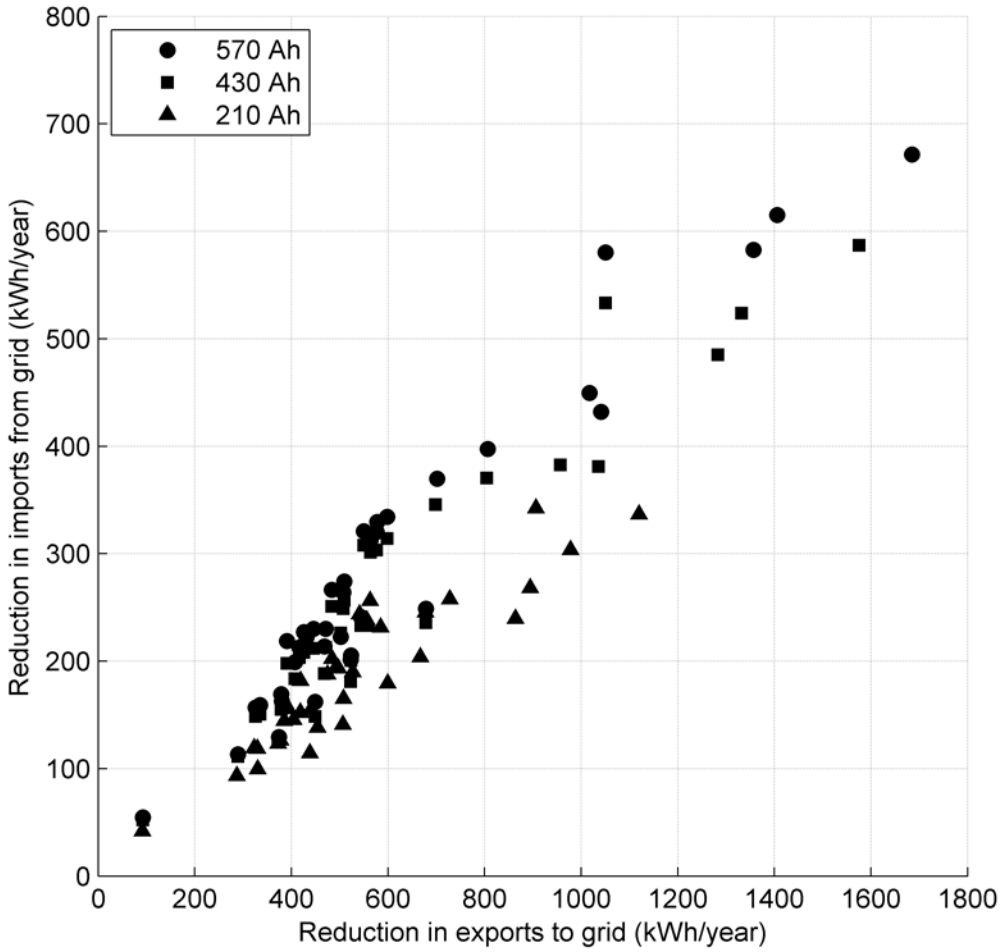
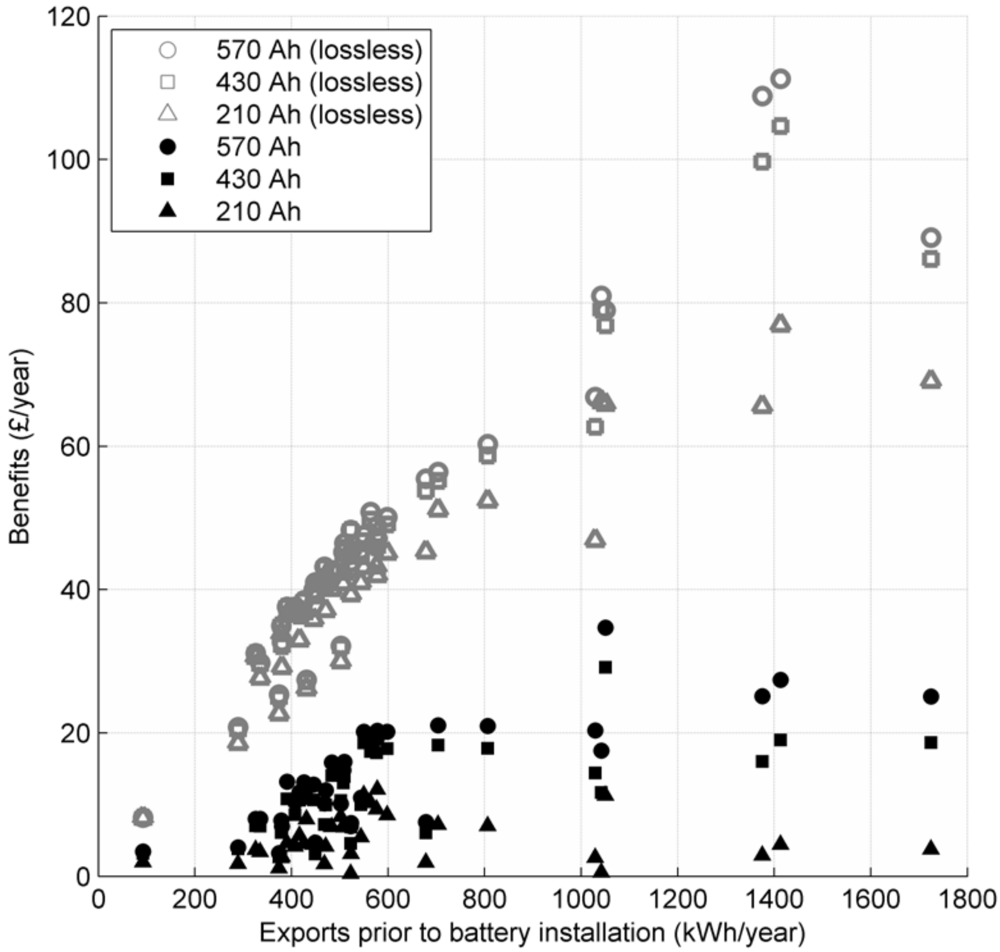


Figure 7 – Reduction in imports and exports associated with realistic batteries of various sizes for multiple dwellings with PV in the UK.



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704 **Figure 8 – Annual benefits for lossless and realistic batteries for multiple dwellings with PV in the UK.**

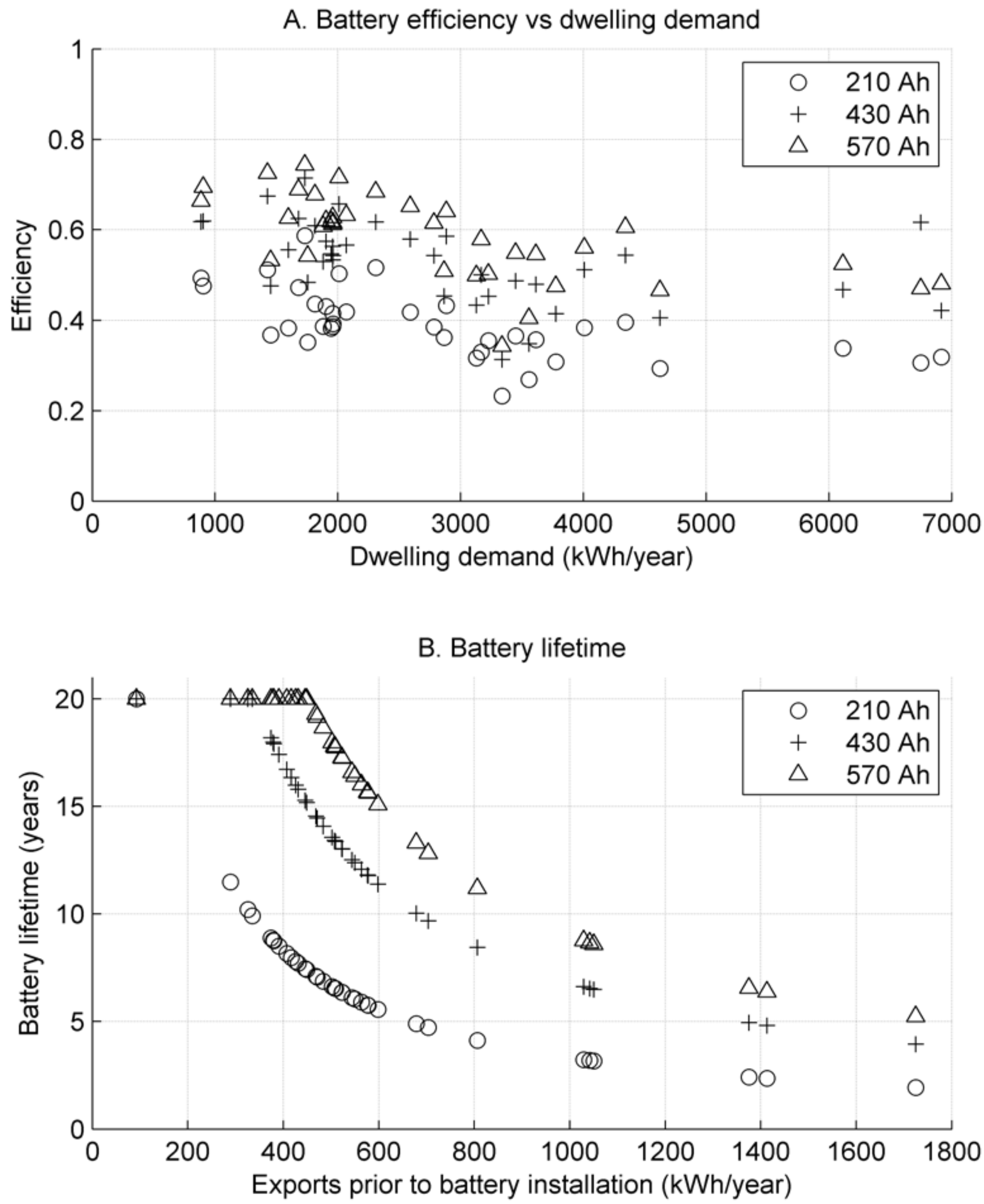

Figure 9 – Battery round-trip efficiency and lifetime.

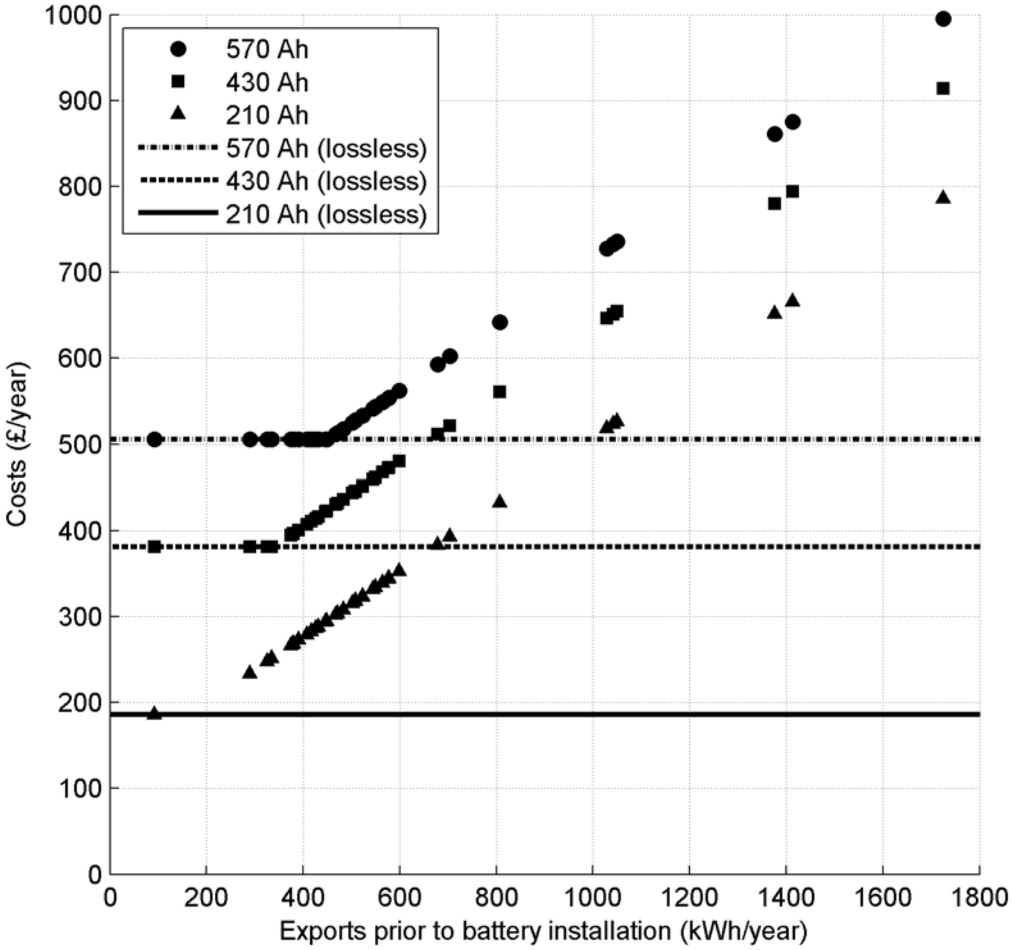

Figure 10 - Annual costs for lossless and realistic batteries for multiple UK dwellings with PV.

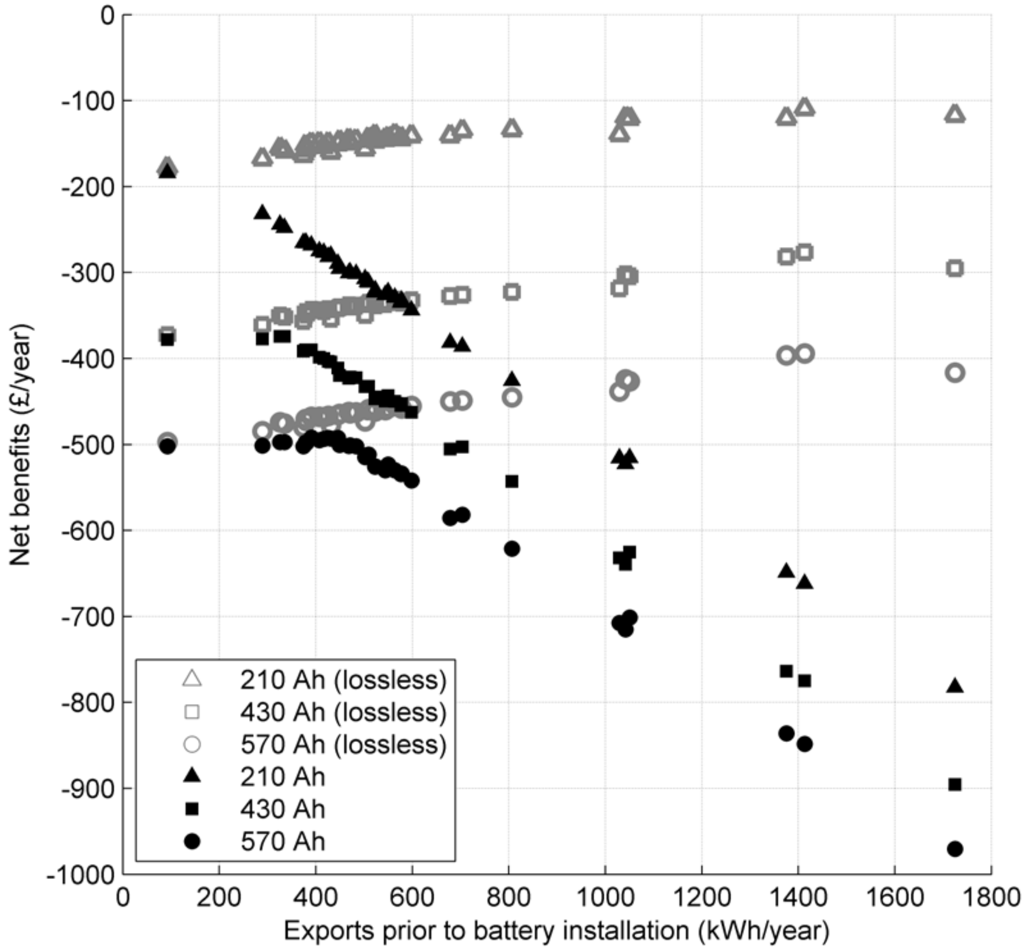

Figure 11 – Annual net benefits for lossless and realistic batteries for multiple dwellings with PV in the UK.

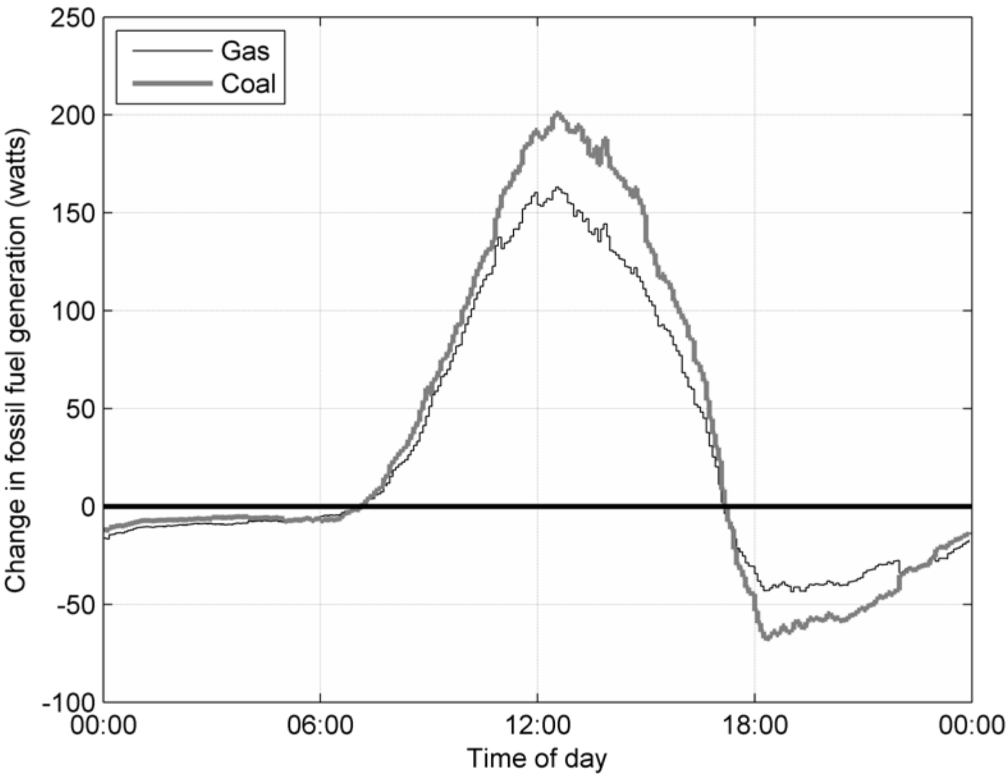

Figure 12 – Change in fossil fuel generation caused by the operation of a realistic 430 Ah battery averaged over the whole year and the multiple dwellings considered here.