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

3
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12
13 6th November 2012

14 **Abstract**

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

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

34 1. Introduction

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

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

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

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

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

72 This paper considers domestic grid-connected PV systems on a current UK feed-
73 in tariff, which consists of a generation price (21.0 p/kWh at the time of writing)
74 paid for generated units, and an export price of 3.2 p/kWh paid for exported units
75 [8]. An import price of 11.8 p/kWh has been assumed, which is a typical value for
76 a domestic consumer on a 'standard' flat-rate demand tariff [9].

77 In this context, occupants with PV systems can benefit financially by using
78 electricity generated by their PV rather than exporting it to the grid [10].
79 Occupants could typically achieve this by changing their behaviour or routines in
80 order to shift their demand to the middle of the day when their PV is generating
81 [11], for example by eating a hot meal at lunch rather than dinner, or with the
82 help of technology such as timers, that can delay when appliances are switched
83 on.

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

89 **3. Method**

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

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

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

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

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

117 **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

118

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

160 The effect of the rate of discharge is considered independently. This is estimated
 161 from data from the manufacturer describing the available battery capacity (in
 162 Ah) as a function of varying rates of discharge [20]. Table 2 reproduces the data
 163 for the 430 Ah battery. This shows that the capacity available is decreased if the
 164 battery is discharged at higher currents. A second, independent coulombic
 165 efficiency is therefore estimated as the ratio of the capacity available at a given
 166 discharge rate compared to the capacity available at nominal discharge rate
 167 (C100). This is shown as a function of discharge current in Figure 2B for the
 168 three battery sizes considered here. In the model, this coulombic efficiency is
 169 applied to the discharge phase. When modelled in this way, the round trip
 170 efficiency for a full charge followed by a full discharge at C100 is approximately
 171 73%. For C10, the round trip efficiency is 44%. Note that these round-trip
 172 efficiencies are for illustration only - the operation of the battery in the model
 173 does not use full discharge cycles.

174 **Table 2 – Discharge characteristics of the 430 Ah battery at varying rates of discharge at 25 °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%

175

176 **3.4. Calculation of power flows**

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

183 **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.
$\eta_{discharge}$	Battery coulombic efficiency due to rate of discharge.
t	Time (hours).

184

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

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

195
$$P_{pv} > P_d \text{ and } SOC < SOC_{max}$$

196 The battery is disconnected when either the minimum state of charge SOC_{min}
197 (60%) or maximum state of charge SOC_{max} (100%) is reached. This constraint has
198 been imposed in order to ensure maximum battery life as per the manufacturer's
199 recommendations [20].

200 The battery charging current is then calculated as:

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

201 Equation 2

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

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

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

205 Equation 3

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

208 State of charge in time interval i is then:

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

209 Equation 4

210 The battery is discharged when the following conditions are met:

211
$$P_{pv} < P_d \text{ and } SOC > SOC_{min}$$

212 In which case the battery discharge current is given by:

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

213 Equation 5

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

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

217 Equation 6

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

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

219 Equation 7

220 **3.5. Calculation of economic benefit of battery operation**

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

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

225 Equation 8

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

231 $\Delta c(i)$ is the change in costs to the occupant in time interval i associated with the
232 battery. This is the difference between the cost of electricity consumed within the
233 dwelling with the battery compared to the equivalent cost of electricity without
234 the battery. For example, if the battery reduced imports in time interval i , then
235 $\Delta c(i)$ would be negative, as costs would be reduced.

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

239 **3.6. Description of data used in the analysis**

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

246 The study uses data from two of the Domestic Field Trail's sites. The first site
247 consists of data from 22 dwellings, and the second site consists of data from 15
248 dwellings. Annual irradiances for the two sites were 894.7 kWh/m², and
249 892.8 kWh/m², which are quite typical for the UK [22].

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

254 **3.7. Battery inverter**

255 The battery inverter is based on the SMA Sunny Backup 5000 [13], which
256 includes battery charge regulator and power electronic converter. The efficiency
257 of the inverter is modelled on the efficiency curve provided in this product's
258 manual. The inverter has a peak efficiency of 95.4% and efficiency of more than
259 91% throughout most of its operating range. Note that this efficiency applies to
260 charging as well as discharging. The inverters are sized for the maximum
261 discharge current of the batteries multiplied by the battery voltage, giving the
262 inverter sizes shown in Table 1.

286 **3.9.1. Production impacts**

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

300 The production impacts of lead-acid batteries per kg of battery weight in terms of
301 greenhouse gases, metal depletion, and fossil fuel depletion are 0.9 kg CO_{2eq},
302 0.4 kg Fe_{eq}, and 0.3 kg oil_{eq} respectively [7]. The contribution to greenhouse gases
303 and fossil fuel is predominantly associated with the extraction and processing of
304 lead and the polypropylene used in the battery production. The contribution to
305 metal depletion is dominated by the lead within the battery. Note that this
306 approach assumes a mix of virgin and recycled materials is used in the battery
307 production, based current norms, as described by McManus [7].

308 **3.9.2. In-use impacts**

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

320 To calculate how the changes in demand throughout the day associated with
 321 adding the battery to the PV system can be expected to result in changes in
 322 generation from fossil fuel plant, data from the UK balancing mechanism reports
 323 [32] was used to calculate the 'responsiveness' of gas and coal generation to
 324 historic changes in demand for each five-minute period in 2009 to 2011.
 325 Responsiveness here refers to the change in generation (in kWh) that is
 326 associated with a change in demand of 1 kWh.

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

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

335 Equation 10

336 Where:

337 $\overline{\left(\frac{\Delta P_{gen}}{\Delta P_{total}}\right)}_h$ - weighted average responsiveness of electricity generated by coal or gas
 338 plant to unit changes in total electrical demand during the time periods in set h
 339 (h_1 to h_n).

340 $\Delta P_{gen}(i)$ – increase in average electrical power generation from gas or coal
 341 generating plant during period i .

342 $\Delta P_{total}(i)$ – increase in average electrical power generation for whole electrical
 343 grid during period i .

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

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

349 Equation 11

350 Where:

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

353 $\Delta P_{net}(i)$ – net change in electrical demand in time period i due to battery
 354 operation (compared to PV system without battery).

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

359 **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

360

361 4. Results and Discussion

362 4.1. Battery operation for a single system over a single day

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

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

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

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

393 4.2. Cost benefit using realistic battery model

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

399 Figure 7 shows how the realistic battery results in reductions in imports from
400 the grid and reductions in exports to the grid, for the systems and batteries
401 considered here. The reduction in imports are smaller than the reduction in
402 exports, due to losses in the battery. The gradient of the lines that pass through
403 the data points gives an indication of how many units of exported electricity are
404 used to provide one unit of avoided imported electricity. A least squares fit
405 through the data results in gradients of 2.14 (0.0482), 2.29 (0.0575), and 2.83
406 (0.0698) for the 570 Ah, 430 Ah, and 210 Ah batteries respectively (standard
407 errors in brackets). These gradients can be compared to the ratio of the import
408 price to the export price, $11.8/3.2 = 3.69$. Provided the gradient is smaller than
409 the import export price ratio, then the batteries can be expected to produce a
410 benefit in terms of savings on electricity bills.

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

418 The low benefits shown in Figure 8 are due to the battery inefficiencies which
419 are shown in Figure 9A. This shows annual round-trip efficiencies for the
420 different dwellings and battery size configurations. The round-trip efficiency is
421 calculated here as the total energy out of the battery inverter over the total
422 energy into the battery inverter. The mean round trip efficiency values are
423 39.1 % for the 210 Ah battery, 53.0 % for the 430 Ah battery, and 58.5 % for the
424 570 Ah battery.

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

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

436 **4.3. Cost benefit for a lossless battery**

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

446 In keeping with the assumption of a lossless battery, the battery is also assumed
447 not to experience any wear, and as such there is no effect on costs associated
448 with increasing annual exports (an indication of how much the battery is used).
449 Equipment lifetimes are therefore optimistic: 20 years for the battery, and 10
450 years for the inverter. This results in annualised costs of £186.2/year,
451 £381.2/year, and £505.3/year for the 210 Ah, 430 Ah, and 570 Ah battery systems
452 respectively. These are illustrated for comparison alongside the realistic battery
453 costs in Figure 10. Note that the minimum state of charge for the lossless battery
454 is kept the same as that for the realistic battery (60%).

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

462 Figure 11 shows the resulting net benefit of the lossless battery (grey markers),
463 again alongside the equivalent net benefits of the realistic battery (black
464 markers). It is clear that the costs are considerably larger than the benefits for
465 all of the systems considered here, even when assuming a lossless battery with
466 optimistic lifetime estimates. The battery results in a net financial loss to the
467 occupant of around £100/year for the smallest lossless battery, increasing to over
468 £400/year for the largest lossless battery considered here. It appears therefore
469 that there is no economic case for the use of lead-acid batteries for the systems
470 and specific commercial opportunity considered here, even for idealised lossless
471 batteries with optimistic lifetimes.

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

475 **4.4. Environmental impact**

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

479 **Table 5 – Battery weights and production impacts.**

Battery Capacity (Ah)	Weight per cell (kg)	Number of cells in battery	Total battery weight (kg)	Production impacts		
				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

480

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

491 The combined annual production and in-use impacts are now considered. Table 6
 492 shows the combined impacts associated with adding a 430 Ah battery to a
 493 3.29 kW_{peak} PV system. These results are comparable to the case of adding a
 494 battery to a modern 4 kW_{peak} PV system. Not unexpectedly, metal depletion
 495 impact is dominated by battery production, while climate change and fossil fuel
 496 depletion impacts are dominated by battery use.

497 **Table 6 – annual production and in-use impacts for 430 Ah battery with 3.29 kW_{peak} PV system. Standard**
 498 **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)

499

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

508 To put these results into perspective, the total annual climate change impact for
509 this battery has an equivalent impact in terms of kg CO_{2eq}/year as driving
510 4362 km in a 'good' (180 g CO_{2eq}/km) UK petrol vehicle [33]. Alternatively, using
511 the same assumptions regarding responsiveness of fossil fuel plant as detailed in
512 section 3.9.2, it can also be equated to an average 2009 UK household
513 (4460 kWh/year) increasing annual electricity consumption by 946 kWh, an
514 increase of 21%.

515 **4.5. Target capital costs**

516 The theoretical maximum benefit to the occupants considered here is 11.8 p/kWh
517 – 3.2 p/kWh = 8.6 p per kWh of otherwise exported electricity. The mean annual
518 exports for the 37 systems considered here was 605 kWh/year, which gives a
519 theoretical maximum benefit of £52 per dwelling per year. Assuming a modest
520 discount factor of 4% over 20 years, this results in a target up-front capital cost
521 of £707 for the battery system to break even. To put this into perspective, note
522 that the cheapest battery system considered here (210 Ah with optimistic
523 lifetimes) has an equivalent up-front capital cost of £3296.

524 **4.6. Comparison with feed-in tariffs from other countries**

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

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

541 The findings are also relevant to PV systems installed from late 2012 in the
542 Australian states of Queensland [35], Victoria [36], and Western Australia [37].
543 These states have feed-in tariffs with export prices of ~ 8 cAUD/kWh, which is
544 17 cAUD/kWh (≈ 10.93 p/kWh) less than a typical import price of 25 cAUD/kWh.
545 The import export price ratio is therefore 3.13 , which is again lower than the UK
546 price ratio (3.69). The results of this paper are therefore also applicable to
547 Australian PV systems installed from late 2012 onwards.

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

554 **5. Conclusions**

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

562 The results indicate that there is no economic case for the use of lead-acid
563 batteries for the systems considered here, even for idealised lossless batteries
564 with optimistic lifetimes. The realistic battery model developed here produced
565 mean round trip efficiencies of 39.1 %, 53.0 %, and 58.5 % for 210 Ah, 430 Ah,
566 and 570 Ah lead-acid batteries respectively. Unsurprisingly, when these
567 efficiencies and realistic lifetimes are accounted for, the financial losses are
568 considerably worse. For the batteries considered here, losses approaching
569 £1000/year can be expected for a 570 Ah added to a 3.29 kW_{peak} PV system.

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

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- 678

679 **8. Appendix**

680 **Table 7 - Weighted average change in electricity generated by coal to unit changes in total electrical demand**
 681 **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

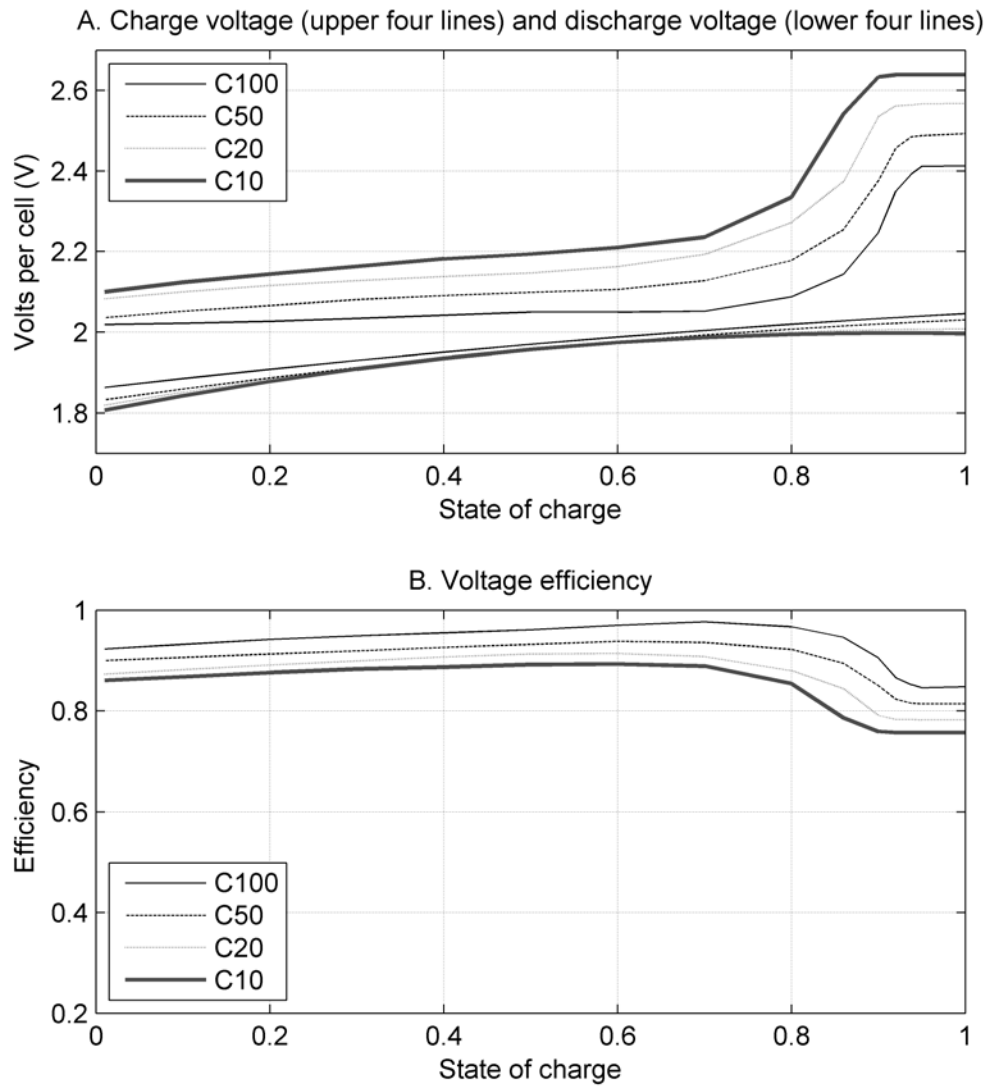
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683 Table 8 - Weighted average response in electricity generated by gas (CCGT) to unit changes in total
684 electrical demand in GB electricity market (data from 2009 to 2011).

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

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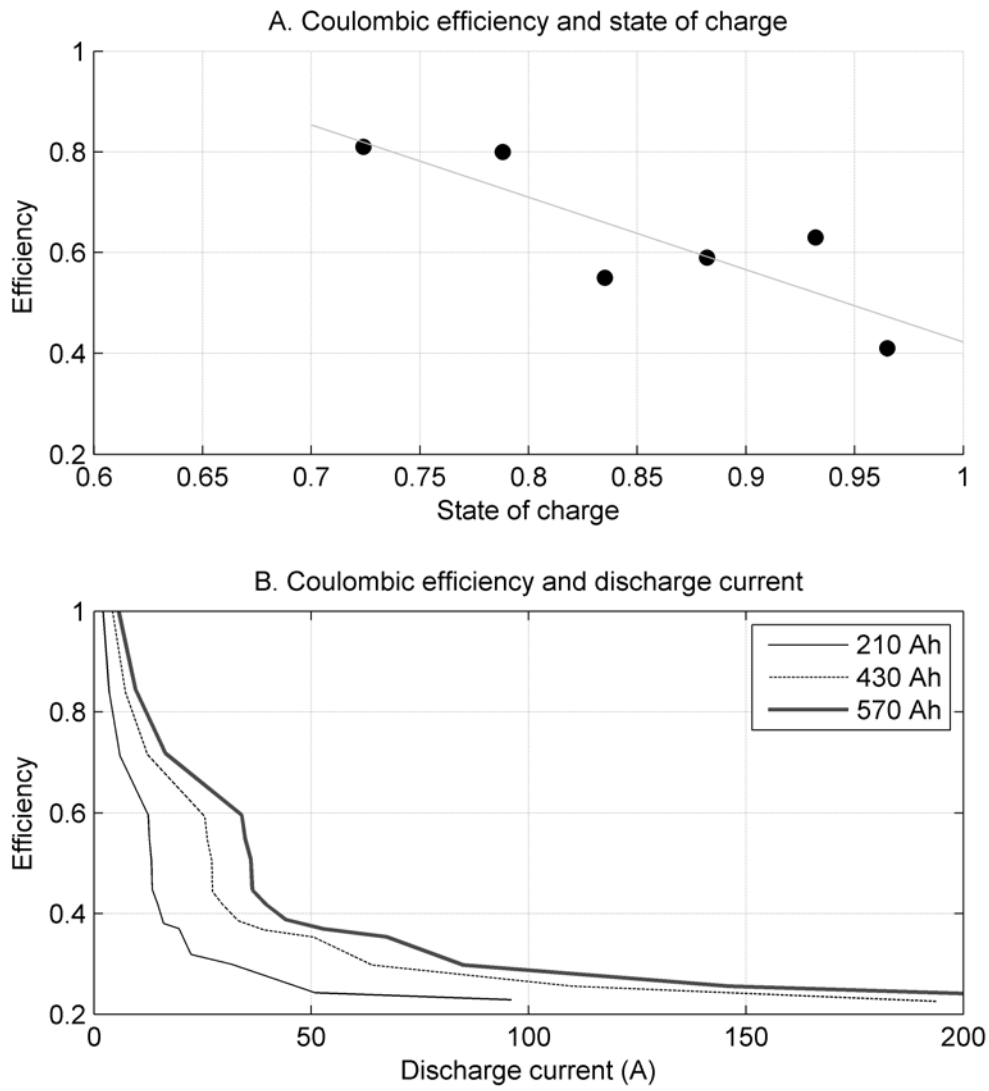
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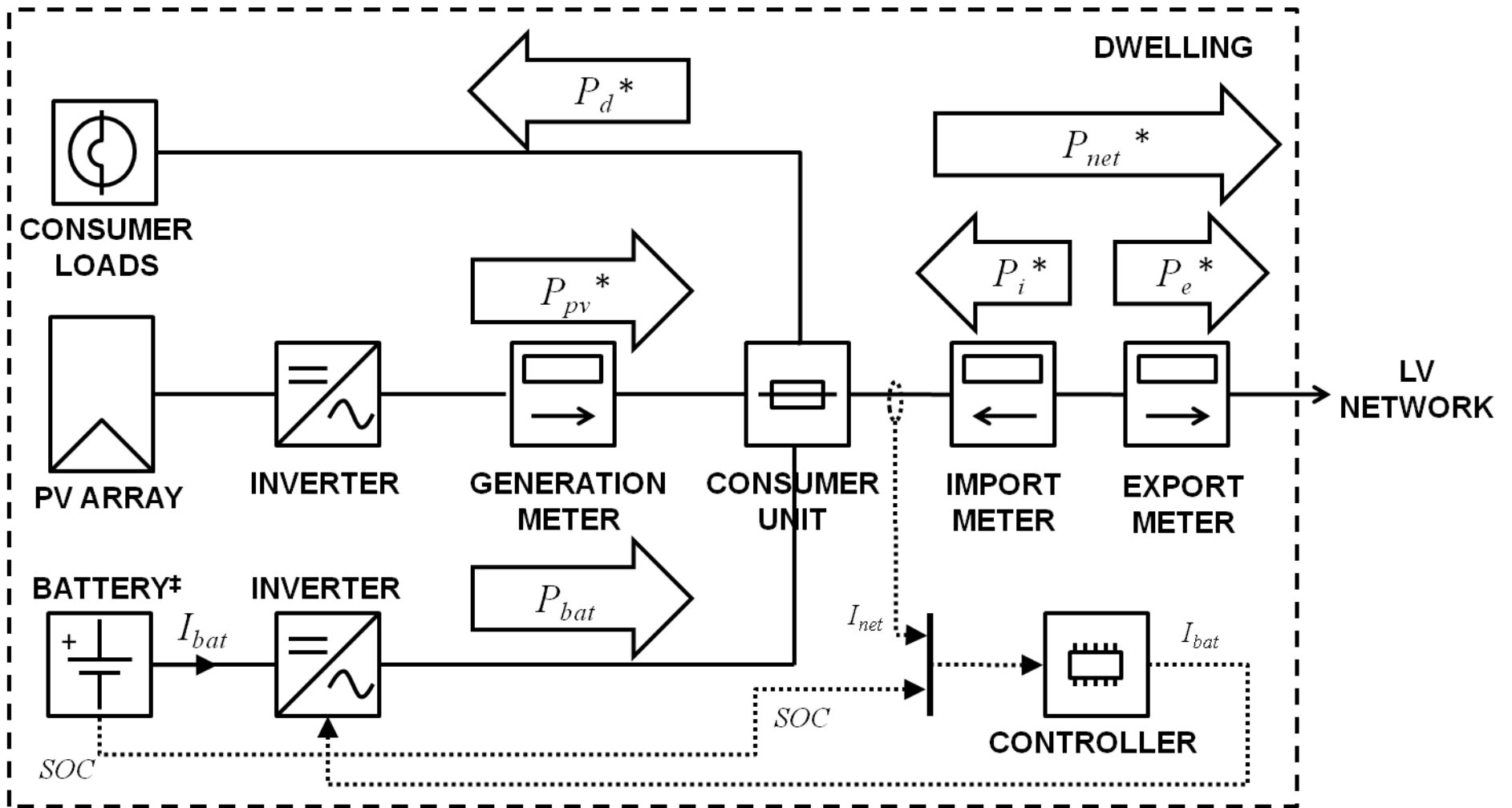
688 **Figure 1 – Voltage efficiency used in the battery model.**

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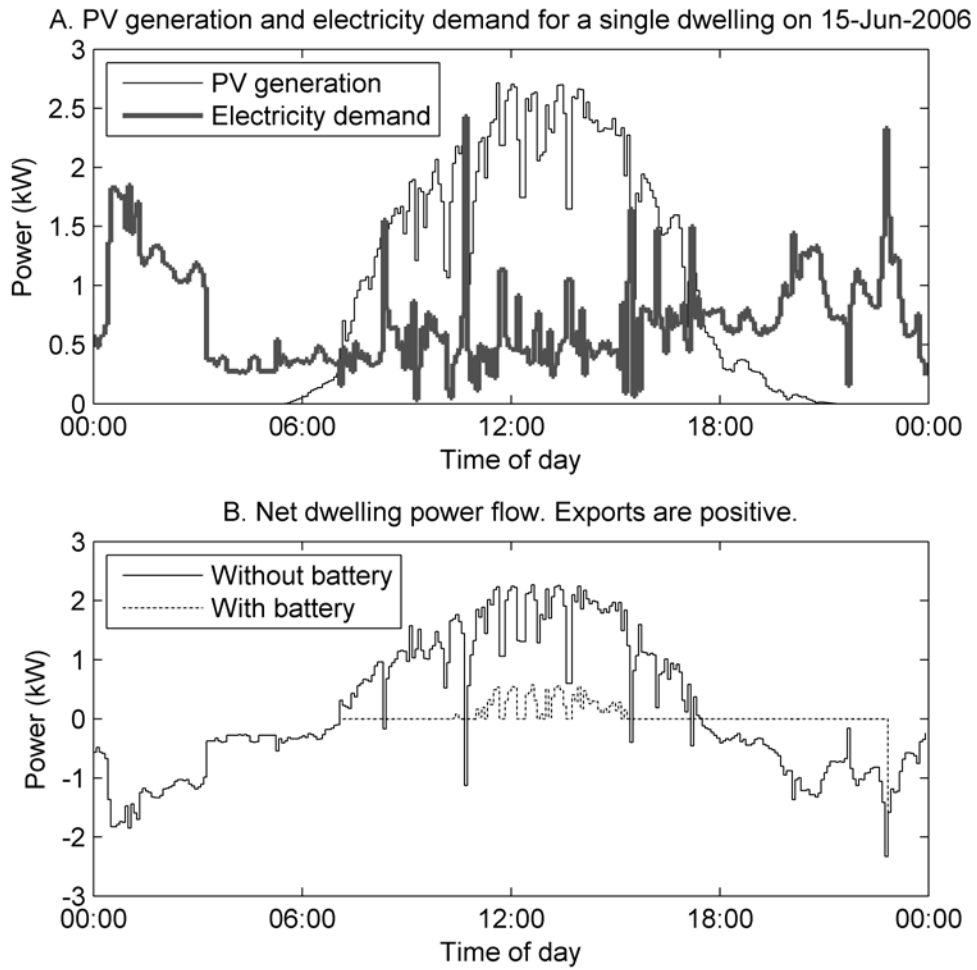
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691 **Figure 2 – Coulombic efficiency used in the battery model.**



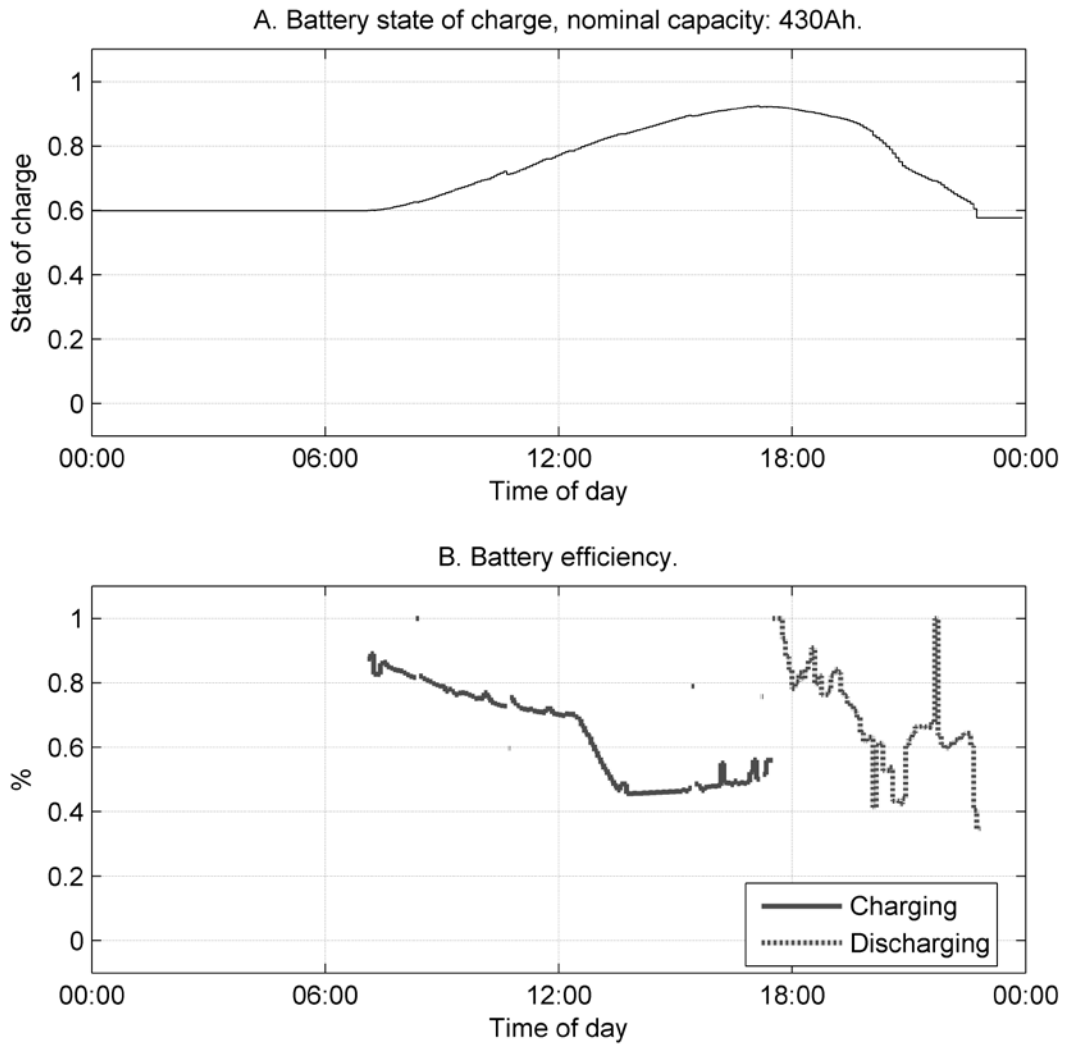
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693 Figure 3 – One-line diagram of a fully metered PV system with battery storage.



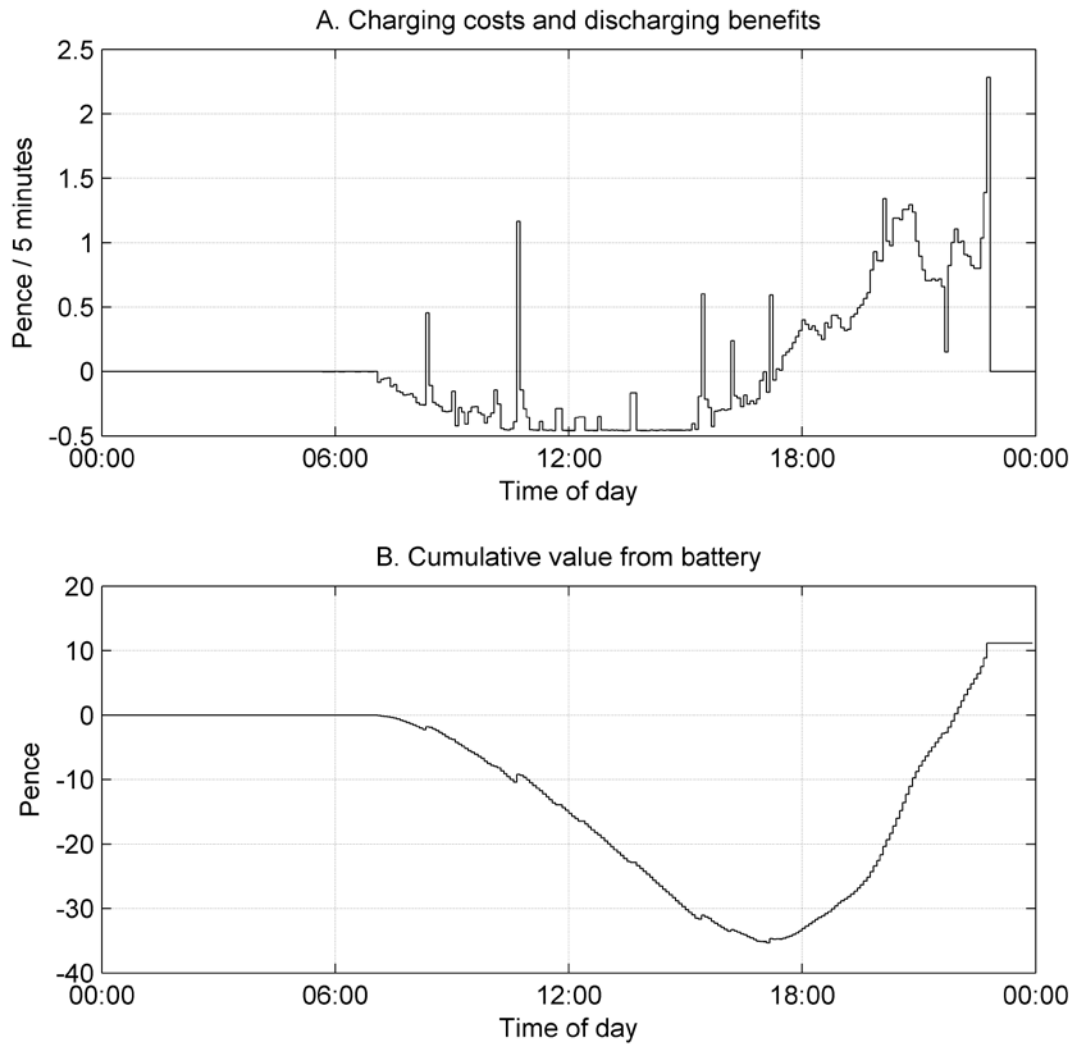
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695 **Figure 4 – PV generation, dwelling demand, net power flow to the grid, before and after battery.**



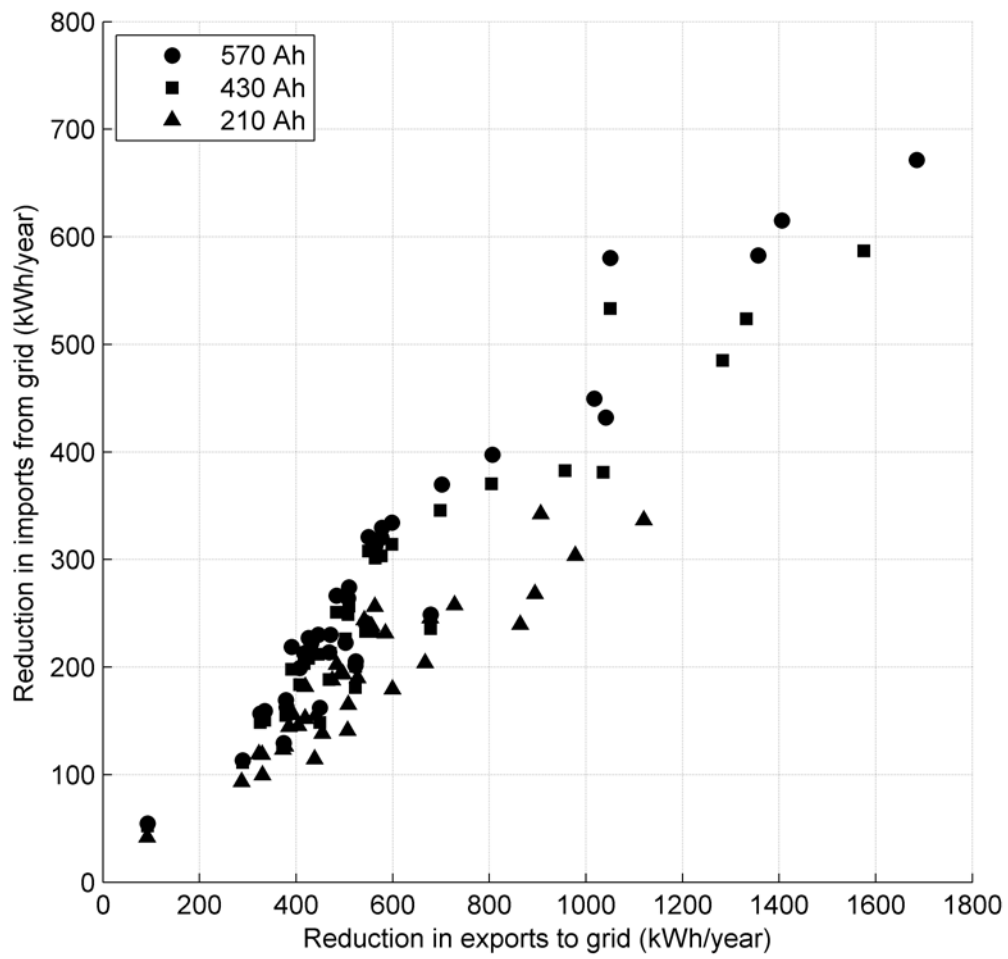
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697 **Figure 5 – Battery state of charge and efficiency.**



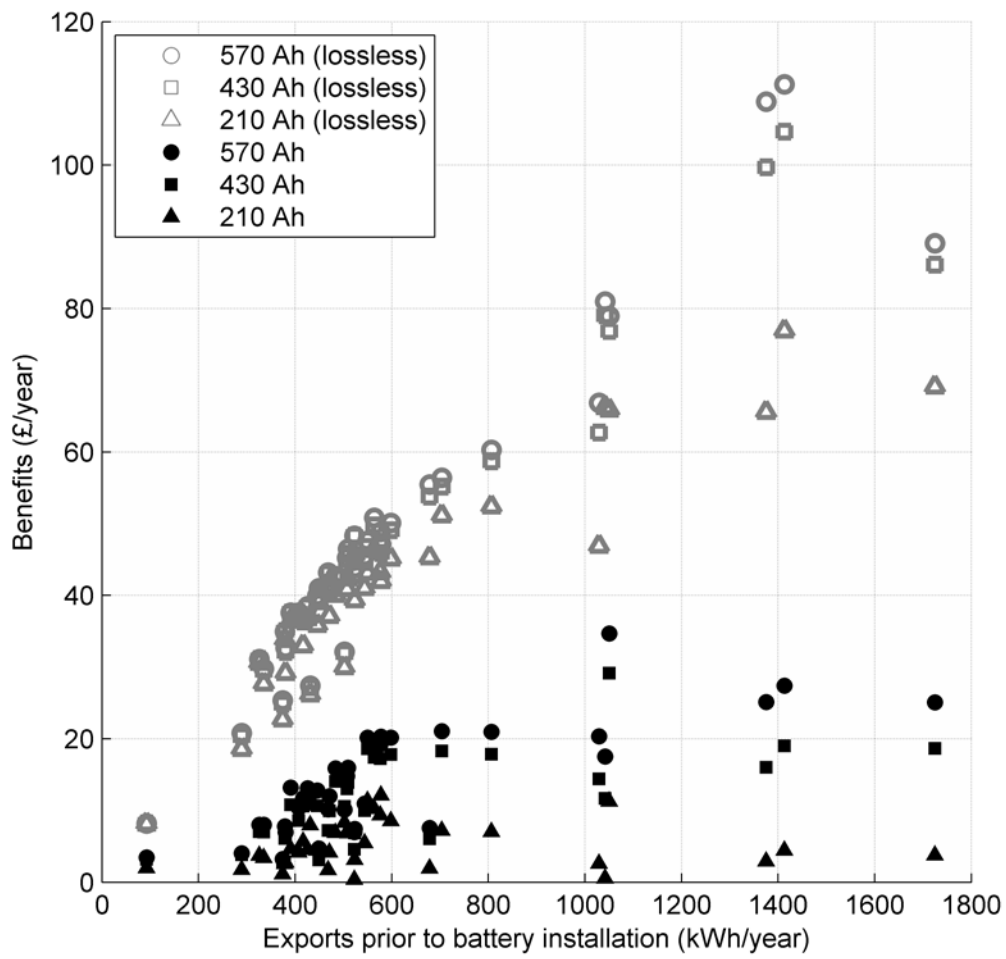
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699 **Figure 6 – Cost benefit over the course of a single day.**



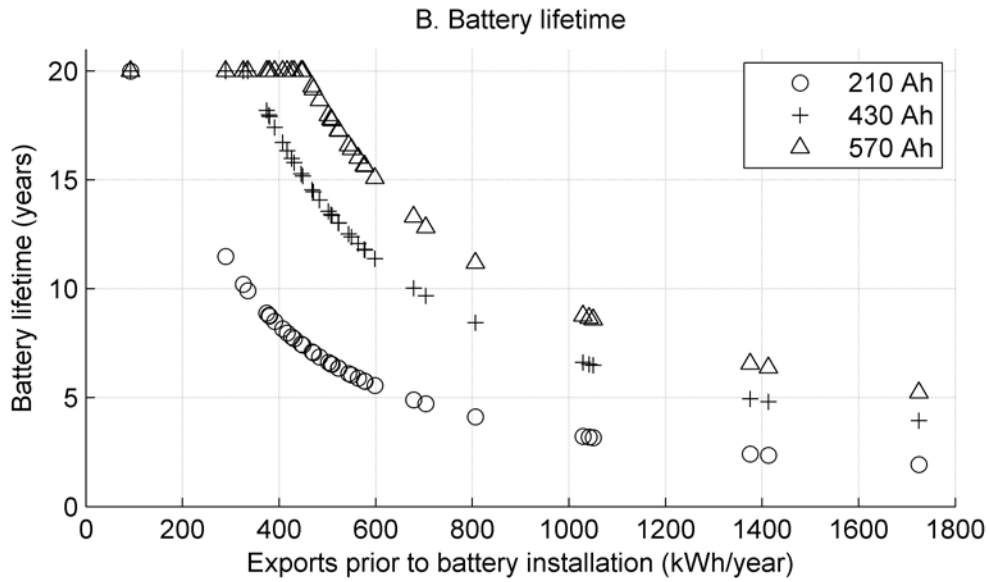
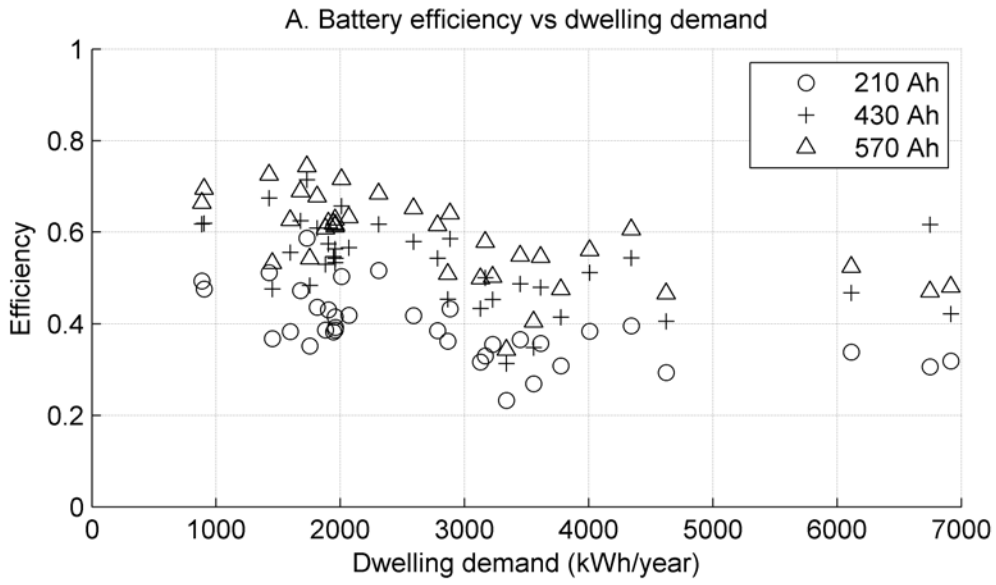
700

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



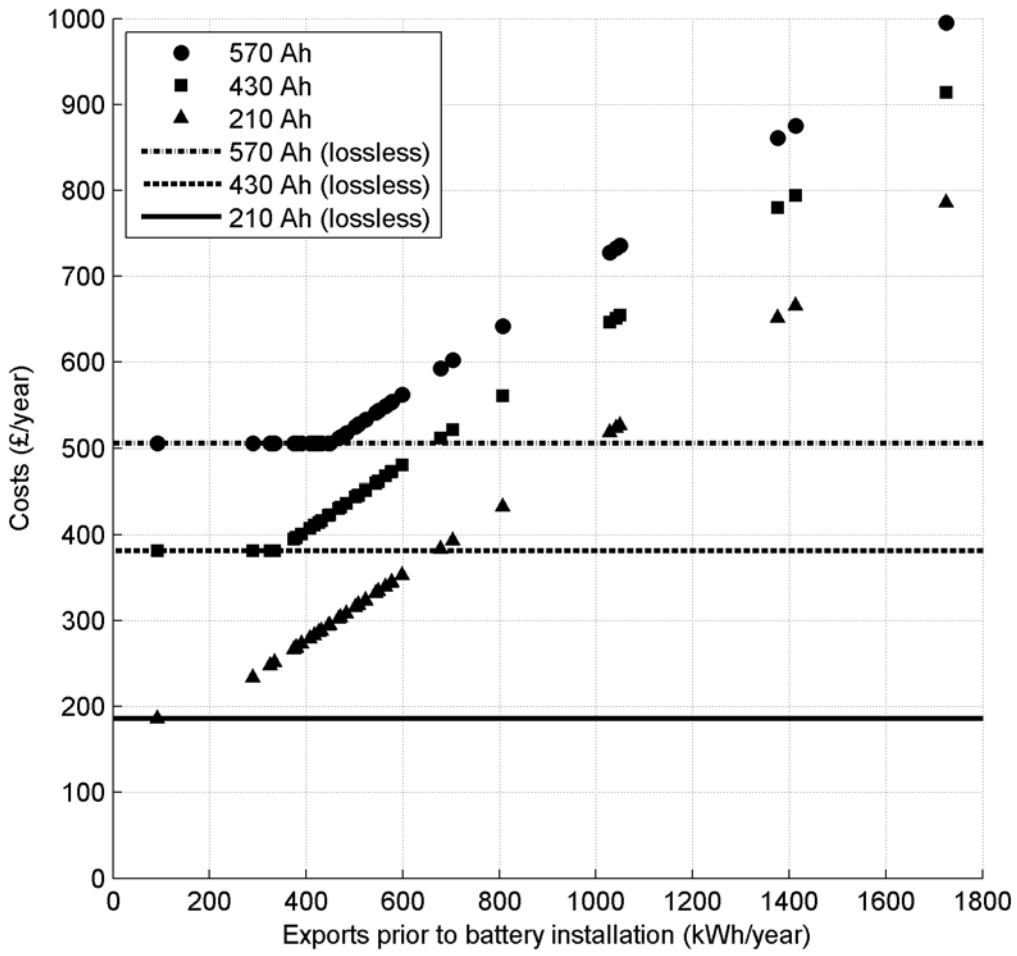
703

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



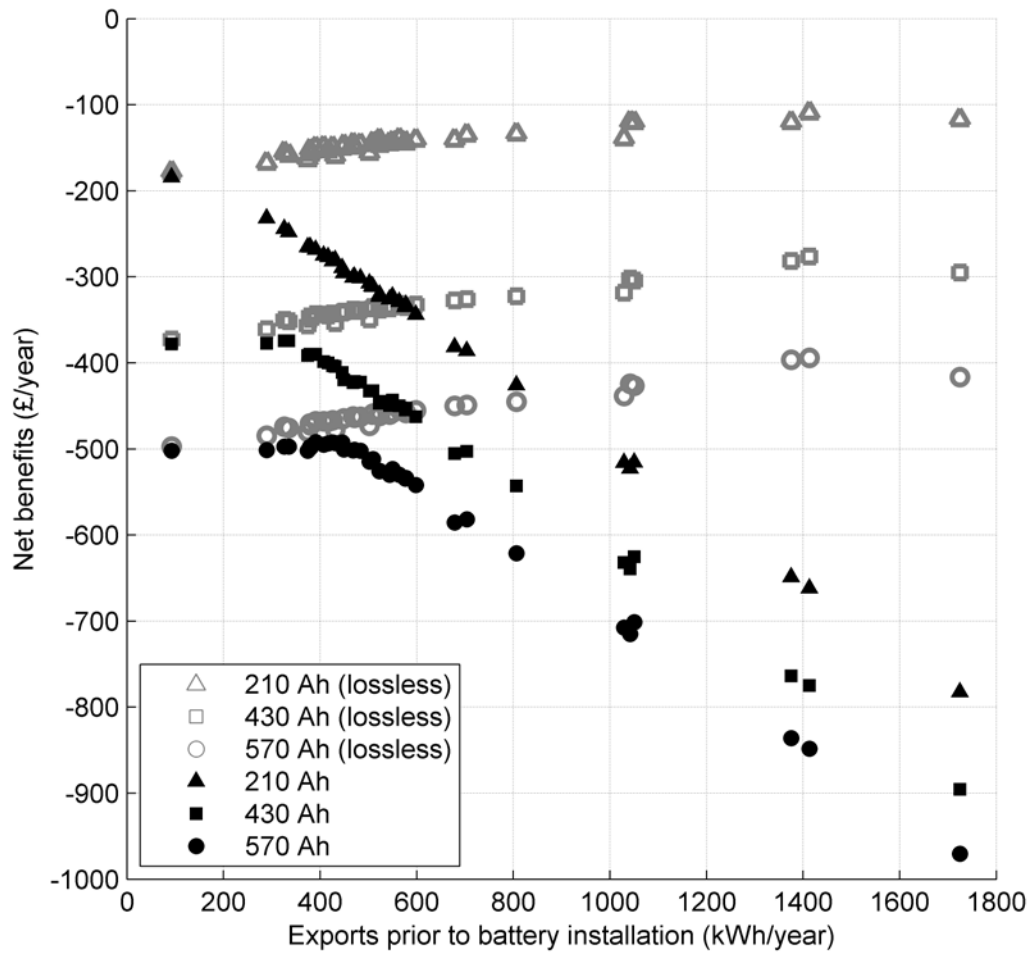
705

706 Figure 9 – Battery round-trip efficiency and lifetime.



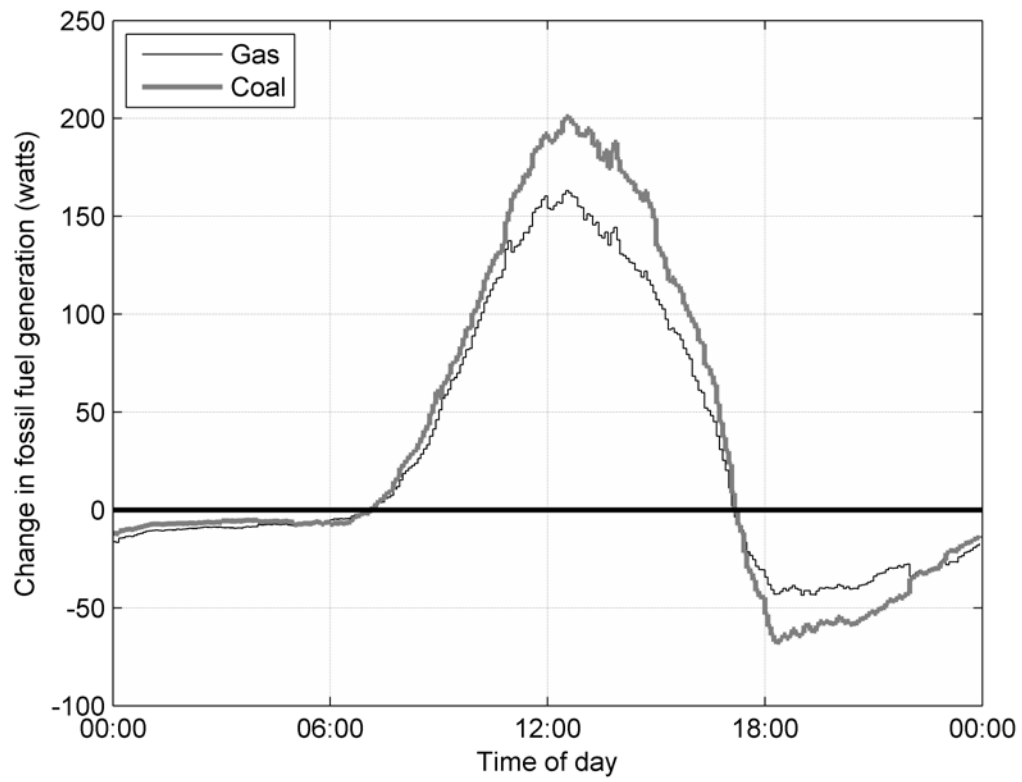
707

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



709

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



711

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

714

715