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Lifetime prediction and sizing of lead–acid batteries for microgeneration storage applications

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Abstract: Existing models of microgeneration systems with integrated lead–acid battery storage are combined with a battery lifetime algorithm to evaluate and predict suitable sized lead–acid battery storage for onsite energy capture. Three onsite generation portfolios are considered: rooftop photovoltaic (2.5 kW), micro-wind turbine (1.5 kW) and micro combined heat and power (1 kW). With no embedded energy storage, the dwelling exports energy when the microgeneration system generates excess power leading to a high level of generated export throughout the year. The impact that the size of installed battery has on the proportion of the generated export that is reserved onsite, along with the annual energy discharged per year by the energy store is assessed. In addition, the lifetime algorithm is utilised to predict corresponding lifetimes for the different scenarios of onsite generation and storage size, with design tables developed for expected cost and weight of batteries given a predicted generated export and lifetime specification. The results can be used to indicate optimum size batteries for using storage with onsite generation for domestic applications. The model facilitates the choice of battery size to meet a particular criteria, whether that be optimising size, cost and lifetime, reducing grid export or attempting to be self-sufficient. Suitable battery sizes are found to have lifetimes of 2–4 years for high production microgeneration scenarios. However, this is also found to be highly variable, depending on chosen microgeneration scenario and battery size.

1 Introduction

Tarbase is a Carbon Trust/ESPRC funded project looking at suitable technologies and adaptations to achieve a 50% reduction in the carbon emissions of buildings by the year 2030. An important factor in attempting to achieve these targets (and likewise other targets such as the UK Government call for net-zero carbon buildings by 2016 [1]) is the role that onsite micro-generation may play. The idea of building-integrated 'renewable energy systems (RES)', that use one or more onsite generation technology, has been researched in considerable detail [2, 3]. There have also been several studies on the use of electrical storage with such systems [4, 5], reducing both the energy that would otherwise be imported from the electrical grid, and reducing the energy exported to the grid. Such considerations become particularly important when looking at individual dwellings with RES unable to match the highly-variable demand profile of the particular dwelling. Furthermore, if a building is to be autonomous from the grid [6] (which may be desirable from an energy security perspective or a carbon-savings perspective), electrical storage is vital. Lead–acid batteries are often specified with such systems [7] due to their reasonable annual performance in dealing with irregular loads, their availability and also the fact that they are largely recyclable. However, understanding the detrimental effects of irregular loads on the performance of lead–acid batteries cannot be understated [8, 9].

There is little in the way of guidance on battery sizing, particularly with respect to battery lifetime for a specific portfolio of onsite microgeneration and also with respect to how battery size impacts on latent grid export. The study reported here investigates three onsite microgeneration scenarios with five proposed battery sizes and quantifies the effect on lifetime of the proposed lead–acid battery systems. A small battery with a large amount of onsite generation will typically have a short lifetime. Therefore it is desirable to know how big a battery needs to be to ensure, for a given microgeneration portfolio and load profile system, an acceptable lifetime and annual performance. Typically, dwellings will be limited by the maximum physical size of the battery and capital cost, so defining 'rules-of-thumb' for optimum storage size would be advantageous for householders, engineers, policy makers and architects, interested in using onsite generation to satisfy the targets of low-carbon buildings.

For the purposes of this paper, 'RES' shall refer to three generation technologies, namely photovoltaic (PV) panels, micro-wind turbines and micro-combined heat and power (CHP), though the latter is not strictly a renewable source.

2 Micro-generation scenarios

The work described here follows on from a previous study by the authors defining a microgeneration system model that includes energy storage [10], which estimates the efficiency of a specified lead–acid battery in taking a given export profile and storing it onsite. The model requires input describing the annual electrical load profile of the dwelling (at a minutely temporal resolution), the onsite generation profile (ideally at the same temporal resolution, though hourly is usually sufficient for PV and ten-minutely for micro-wind turbines) and battery specifications (Table 1).

The model then allows the battery to charge or discharge (at specified rates), depending on the balance between onsite generation and electrical demand at any given time. If the onsite generation is insufficient at that time, then the battery discharges. If the battery is completely discharged, then the grid is required to meet the demand. The model can thus be summarised by the following steps:

- The power reaching the AC bus (Fig. 1) is calculated from the onsite DC and AC power generation (where manufacturers' data is used to estimate the efficiency of converting from DC to AC)
- The surplus or shortfall of power is estimated by comparing the above with the electrical demand profile (nominally, due to need of high temporal (i.e. minutely) resolution, this annual profile is obtained from data or bottom-up profile simulation)
- If surplus exists, the battery is charged (allowing for inefficiencies of AC to DC conversion and charge controller, the latter approximated at 98%)
- If shortfall exists, battery is discharged (allowing for inefficiencies of DC to AC conversion and charge controller)
- The state of charge (SOC) is monitored at all times: if this reaches 20%, the battery is prevented from discharging; if 100% is reached then battery is prevented from charging and remaining surplus will be exported. 'Efficiency' of charge and discharge cycles will depend on the SOC at any given time
- The grid is allowed to satisfy any remaining electrical demand after the above calculation is made (see previous work for more detail [10]).

An example of a typical daily demand output is shown in Fig. 2 (which is taken from the previous study by the authors [10]), with a combination of RES, battery and grid meeting the demand of a dwelling. The model accounts for system losses and inefficiencies of the battery charge–discharge cycle and the charge controllers and inverters used with the battery.

Table 1 Example of required input to describe battery in performance model

voltage across cell, V	2.1
max discharge current, A	200
max charge current, A	100
no. of cells in series	20
no. of batteries in parallel	20
max cell capacity, Ah	50
lower cap acceptable limit	0.2
higher cap acceptable limit	1
inverter power rating, (batt to load), kW	8.4
inverter power rating, (DC to load), kW	2.5
average efficiency of controller, %	98

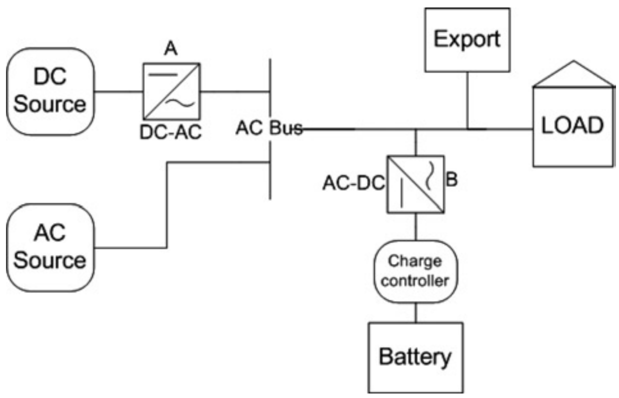

Figure 1 *Proposed configuration for micro-generation with storage*

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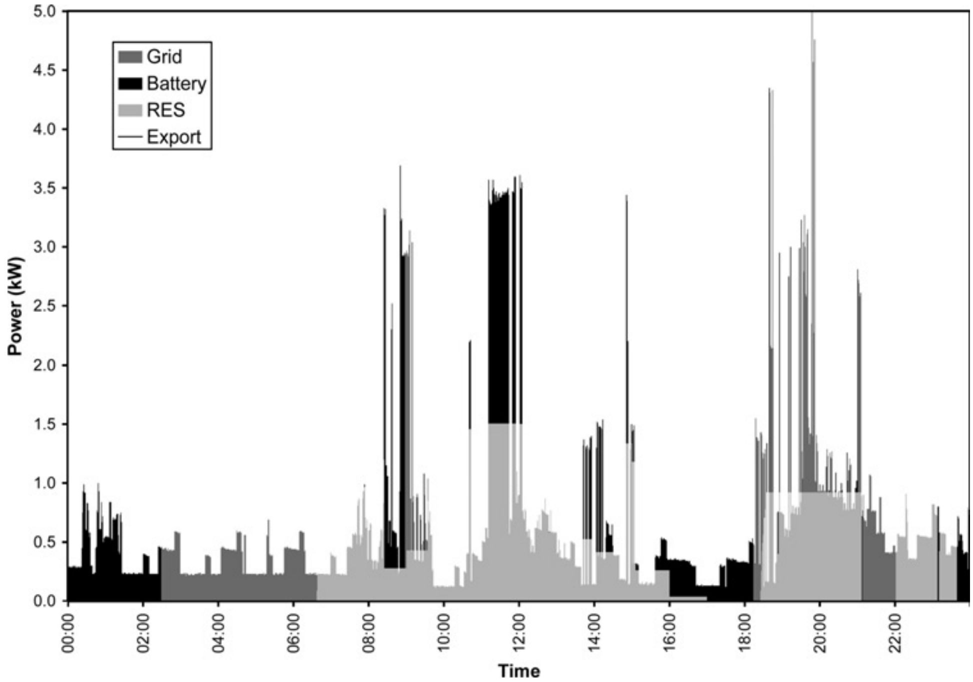

Figure 2 *Example of battery model output for satisfying domestic electrical demand*

The model is used for three defined micro-generation scenarios, namely:

1. 1 kW, Stirling engine CHP, electrical efficiency 15%

2. Monocrystalline 2.5 kW PV panels, 13.5% efficiency, using test reference year climate data [11] to define external temperatures and solar radiation on an hourly basis

3. Combination of the above with a 1.5 kW wind turbine, using ten-minutely windspeed data for an entire year collected at Heriot-Watt University weather station

The above technologies have been modelled [12–14], with the predicted generated energy stored by different battery configurations (definitions of the discussed microgeneration technologies can also be found from these references). Using minutely temporal resolution, rather than hourly or daily data, is vital in evaluating the battery lifetime as short duration, high current discharges contribute significantly to battery degradation. A lead–acid battery will last longer if performing regular low *C*-rate charge/discharge cycles than when having to deal with irregular, high *C*-rate discharges, particularly at low SOC. The estimated annual generation of the described technologies is detailed in Table 2. These estimations are used with demand-side data described elsewhere [15]. This empirical data describes actual energy use in a given dwelling at high temporal resolution, with energy use typical of a UK home (based on annual energy use). This allows an accurate supply-demand matching analysis, with the power requirements to and from the battery assessed every minute.

The export values in Table 2 are relatively high as the onsite generation profile throughout the year will generally often not coincide with the demand profile – this is partly due to the high temporal resolution of the data that picks-up short-duration energy generation. The mismatch between onsite supply–demand is particularly poor with PV generation which occurs during daylight hours when onsite demand is low. The best supply-demand match for the technologies chosen is CHP, as the electricity is produced when people should be present in the building, hence a heating requirement. As a result of this intrinsic matching, grid export for the CHP scenario is only 39% of the total energy generated by the CHP unit, whereas for

Table 2 Summary of onsite generation for described scenarios

Technology	Demand, kwh/yr	Onsite generation, kWh/yr	Available export, kWh/yr	Required import from grid, kWh/yr
CHP	5643	2340	916	4219
PV	5643	2594	1374	4423
PV, Wind and CHP	5643	5206	2751	3189

the other two scenarios ('PV' and 'PV, wind and CHP') this percentage is 53%. The increased percentage of exported energy would suggest a need for a larger battery store and increased charge–discharge requirements of the electrical storage option for the same reduction in annual grid export.

3 Microgeneration and energy storage configuration

It is difficult to determine optimum battery sizes based on empirical evidence as RES with battery storage are not commercially widespread. The sizes of battery chosen range from those deemed suitable for small applications and those that might be necessary for a large RES (this judgement is made from the previous study [10]). Table 3 gives the five battery sizes and specifications chosen in this study.

In all cases, the maximum discharge current is linked to the capacity of the battery, with $C/5$ used for this study, where C is the battery capacity in Ah (this means that, for a 100 Ah battery, the maximum discharge current would be 20 A) [16]. This is recommended to allow an adequate battery lifetime (high C-rate discharges produce poor lifetimes). A similar restriction ($C/10$) is placed on the maximum charge current which, as well as protecting the battery, improves the 'charge efficiency' (high C-rate charging is also inefficient). A lower limit of 20% is placed on the SOC to protect the battery from deep discharges [10].

As a result of the above restrictions, an important factor affecting lifetime is the cumulative energy (in kWh) stored by the battery. The model therefore assumes that a 250 Ah, 42 V battery will have an identical performance to a 500 Ah, 21 V battery (i.e. both batteries have 10.5 kWh of electrical storage). However, if these two batteries had different discharge rates (e.g. one with $C/5$ and the other $C/10$), then the battery with the lower discharge rate will have a longer lifetime.

The chosen battery is modelled in a circuit described in Fig. 1. Through the use of this model and applying an algorithm for defining battery lifetime (Section 4), the five different batteries with the three different RES scenarios are modelled. In particular, this enables a comparison of lifetime and percentage of grid export stored onsite for varying battery size. Rules-of-thumb can be derived for the size of battery that would be suitable, from an energy perspective, for a given microgeneration system.

4 Battery lifetime algorithm

An existing lifetime estimation algorithm [17] is applied to the microgeneration system model to predict battery lifetimes. This algorithm attempts to quantify the effect of long-term operation on the performance of a battery, suggesting time limits to effective operation. While this calculated limit is not a definitive battery lifetime, it does provide an indication for deciding at what point a battery might be (or should be) replaced. In summary, the algorithm places a cumulative lifetime limit on 'effective' ampere-hours of charge delivered by a battery. In the model, at each instant of time (in this case every minute of operation) the effective discharge is the product of the actual ampere-hours delivered and the 'effective weighting' of the discharge. The effective weighting factor is determined from the estimated SOC of the battery at that instant. Fig. 3 shows the variation of the effective weighting factor with SOC. For example, at an SOC of 0.5, removing 1 Ah from the battery adds 1.3 Ah to the lifetime cumulative total. However, at an SOC of 1, removing 1 Ah will result in only 0.55 Ah being added to the effective cumulative total. This would indicate, as is usually assumed, that batteries are best operated at high SOCs to optimise the lifetime.

The algorithm can be used with standard manufacturers' data on lifetime estimates of the expected ampere-hours that a battery will provide over its lifetime at given SOCs. A review of manufacturers' data for deep-cycle lead–acid batteries, for example [18], reveals an approximation that a battery size of Q ampere-hours will deliver (390 Q) effective ampere-hours over its lifetime. This assumption is used in Section 5 with the battery model for varying sizes and configurations of batteries. However, this will only apply to the specific battery under consideration. A battery corresponding to a lifetime of $195Q$ would have half the

Table 3 Summary of chosen battery specifications used in model calculations

Battery size, kWh	Capacity, Ah	Voltage across battery, V	No. of cells ($A \times B$)[a]	Maximum discharge current, A	Maximum charge current, A
5.3	250	21	50	50	25
10.5	250	42	100	50	25
21	500	42	200	100	50
42	1000	42	400	200	100
63	1500	42	600	300	150

[a]this refers to total number of 2.1 V cells in series (A) and parallel (B)

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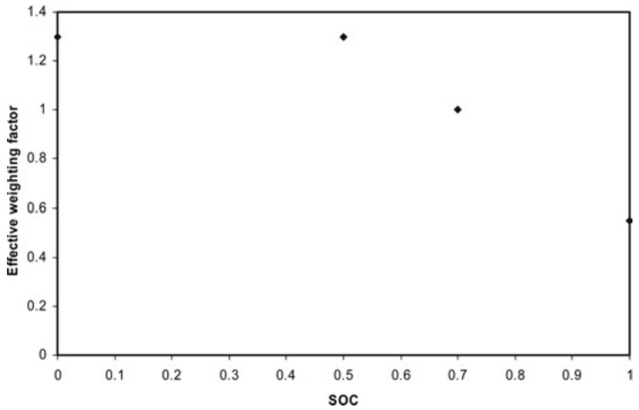

Figure 3 *Relationship between effective weighting factor and SOC of battery used in model*

lifetime if all other parameters were maintained (due to the linear relationship between lifetime and effective ampere-hours being used).

5 Battery model results

Using the microgeneration model, the battery configurations are assessed to determine lifetime and recommendations for optimised size for the three microgeneration scenarios.

5.1 *Effect of available export on battery lifetime*

Fig. 4 plots the available export from each microgeneration configuration (before storage) and the resulting lifetime of the battery, for the five different battery configurations in Table 3, if storage was used with these microgeneration scenarios. The three groupings of data correspond to the three different microgeneration scenarios (as labelled). There is a clear, and intuitive, trend between how much energy the battery is having to process, and the lifetime. Also, the larger batteries show an improved lifetime for a given annual export. This therefore demonstrates (and quantifies) that larger batteries and smaller onsite exports produce longer lifetimes.

If designers approximately know the likely level of export from a RES, Fig. 4 could be used to determine battery lifetime, hence also replacement intervals. For example, if 1000 kWh of energy is being exported from a given house, then the owners might choose a 5.25 kWh battery, lasting ~2 years, or a 10.5 kWh battery, lasting ~4 years.

Fig. 5 shows the results in a different way, giving the change in lifetime with battery size for the different scenarios.

These results show a linear relationship between battery lifetime and battery size and an inverse relationship between available export and lifetime (shown by the curves in Fig. 5, which approximate to the form $y = ax$). This enables the formulation of an approximate design equation

$$T = (329.9/E_e) \times S \qquad (1)$$

where T is the predicted lifetime of the battery (years), E_e is the annual export available from the onsite generation (kWh/year) and S is the size of the battery (in kWh). This design formula is compared with the model results in Fig. 6, with the black line representing the form $y = x$ (which would be an ideal match between the model and the design formula). The results suggest that (1) is a suitable design equation, although it becomes less accurate for smaller batteries (seen by the first few points being below the $y = x$ line). This is partly due to smaller batteries not displacing the same percentage of available export, and so the value for E_e in (1) becomes less suitable to describe the amount of energy being processed by the battery. The two points in Fig. 6 that deviate most from (1) (corresponding to the 5.25 kWh battery) displace just 51% and 62% of the available export, respectively. Therefore it is recommended that (1) should only be used for batteries that are displacing more than,

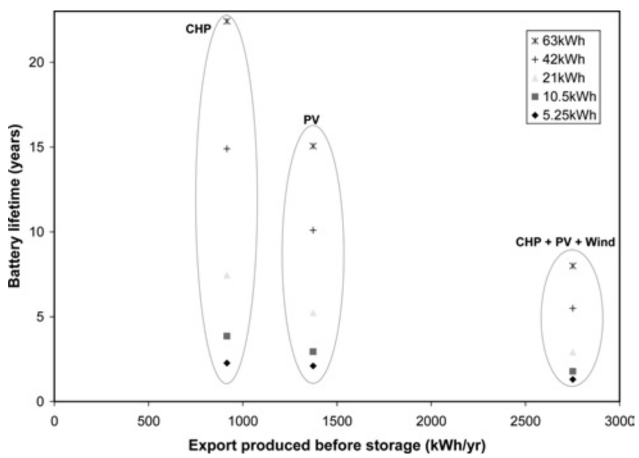

Figure 4 *Lifetime of battery against export produced by RES, for different battery sizes*

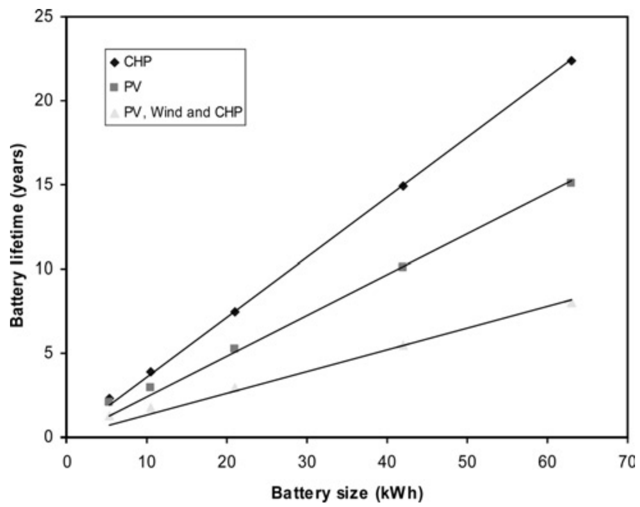

Figure 5 *Graph of battery lifetime against battery size for the three generation scenarios*

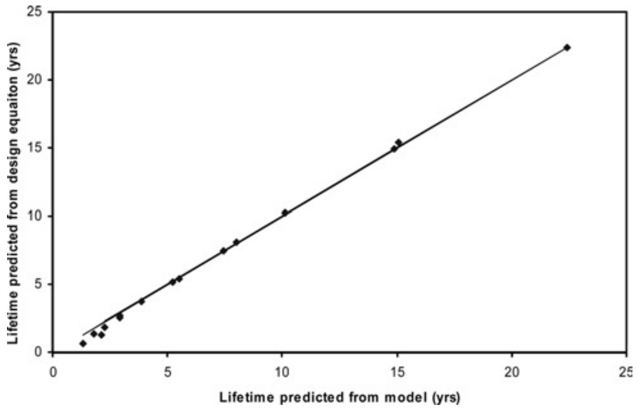

Figure 6 *Comparison of battery 'design formula' and model results*

nominally, 70% of the export. The effect of battery size on displaced export is discussed later in further detail.

Fig. 5 does not show how the different batteries perform in terms of the output of the battery over the course of a year. Clearly, a very small battery might not be able to store all the available export from a site producing a large amount of export. Conversely, an oversized battery will be under-utilised for significant periods of the year if the export is relatively small (as well as being expensive and difficult to locate/install). The next section illustrates a compromise between battery size and lifetime for each microgeneration scenario.

5.2 Power discharged from battery for different onsite generation scenarios

Fig. 7 shows the annual discharge (in kWh) from each battery for each of the three microgeneration scenarios. The significance of this graph is the plateau region that occurs where, once the battery has reached a certain size, there is little (or no) increase in the output of the battery over the course of the year. This implies that, for a given onsite generation profile there is an optimum battery size, beyond which no additional energy is kept on-site that would normally be exported. A larger battery will offer an improved lifetime. For example, from Fig. 5, a 40 kWh battery with the PV scenario, has an estimated lifetime of 10 years and a 20 kWh battery a lifetime of 5 years. Further, the volume required to accommodate the 20 kWh battery will be half that of the 40 kWh battery, maintenance costs will potentially be lower with the smaller-sized battery, and the capital cost of the inverters and associated electrical infrastructure reduced. However, a 20 kWh battery will displace the same amount of onsite generation per year as the 40 kWh battery.

Fig. 7 demonstrates the effect of onsite generation on the defined optimum battery size. For the CHP-only scenario (with onsite generation of 2340 kWh/year), the optimum size of battery would be ~10 kWh (subjective and influenced by economic considerations). The PV scenario (generating 2594 kWh/year) would benefit from a slightly larger battery, between 15 and 20 kWh. Finally, the PV, wind and CHP scenario (generating 5206 kWh/year) would require a larger battery to reach the full annual potential, in the region of 50 to 60 kWh. There would be no discernable advantage from a battery larger than this in terms of export displaced (kept on-site) by the battery.

Fig. 8, shows the percentage of export displaced for the three scenarios and five battery configurations. The plateau now occurs when all the export is being used (so if a 24 kWh energy store absorbs all the export then a 100 kWh battery will not be necessary). This graph can also be used for deciding whether it would be worth increasing a battery size so that it might, for example, displace 100% of the available export rather than 90%. In the case of the largest

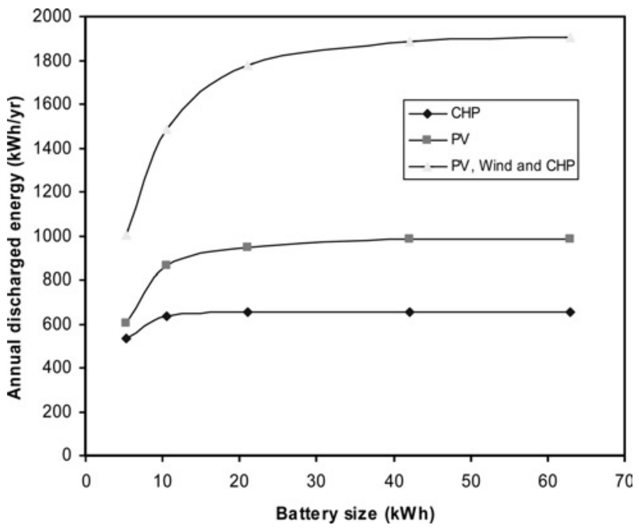

Figure 7 *Annual discharged output of battery for different battery sizes*

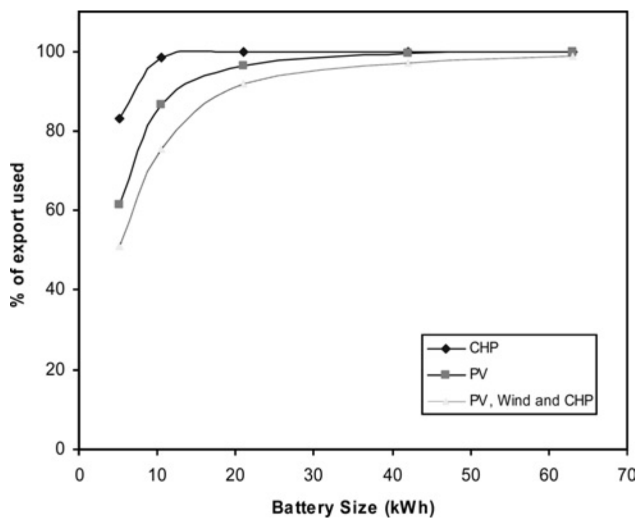

Figure 8 *Percentage of export used by batteries of varying size for the different RES scenarios*

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RES scenario (PV, wind and CHP), moving from a 21 kWh battery to a 63 kWh has increased the percentage of displaced export from 92% to 99% – tripling the battery size has, thus, not had a vast improvement on the annual performance of the battery. For the same situation, the 21 kWh battery would have a lifetime of almost 3 years (Fig. 7), which might be sufficient for a domestic application (particularly when accounting for the cost of a larger battery).

5.3 Lifetime output of battery

Fig. 9 demonstrates the broadly linear relationship between battery size and total discharge over lifetime. This shape is only apparent as, for the majority of the cases, most (or all) of the export is being used throughout the year. Therefore with the plateau reached for relatively small sizes (as with Figs. 7 and 8), all batteries are discharging a similar output per year, but the larger batteries last longer (and so discharge for more years). There are small effects that result in a deviation from this rule. For example, the battery outputs more energy if there is a large amount of onsite generation (hence the data for the PV, wind and CHP scenario having slightly more total discharge over lifetime than the other two scenarios).

5.4 Discussion of C-rate chosen for charge and discharge

As mentioned in Section 3, *C*-rate limitations have been placed on the charge and discharge currents entering/leaving the battery. As a demonstration into the effect of varying the charge current, the model is used to predict battery lifetimes for the 10.5 kWh battery (250 Ah and 42 V) for different charge currents (i.e. not just restricted to $C/10$). The largest microgeneration scenario is chosen (i.e. 2.5 kW PV, 1 kW CHP and 1.5 kW wind), as this should show the largest effect of charge current restrictions (with the other microgeneration scenarios generating smaller charge currents, and so less likely to be restricted by charge current limits of greater than $C/10$). Table 4 compares the results of choosing charge currents of $C/5$ and $C/2.5$ (relating to 50 and 100 A, respectively, for the 10.5 kWh battery) with the $C/10$ (25 A) value used in Section 3. As expected, the higher charge currents absorb more export, and so discharge slightly more electrical energy over the year. There is a small, detrimental effect on lifetime, with the battery now having to process more energy. However, in terms of battery output, the increase from a 25 to 100 A charge current has increased the discharged energy by ~10% (with export to grid reduced by a similar percentage). This would suggest that, with such a small decrease in battery lifetime, the main reason for choosing the $C/10$ limit for charging the battery is purely to protect the battery from high currents – the detrimental effect on lifetime is probably compensated by improved output during the year.

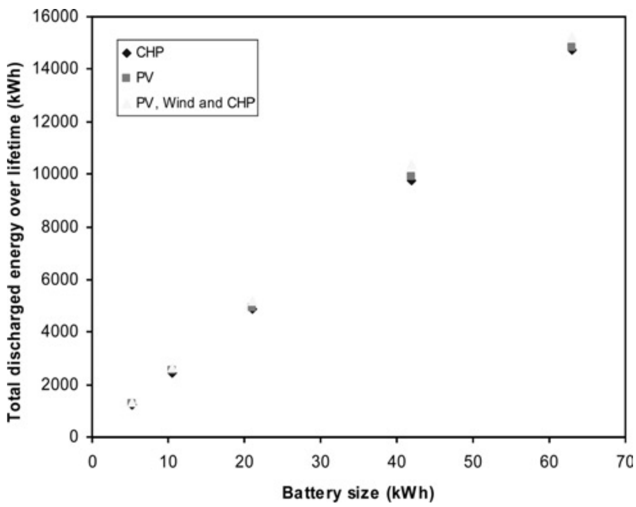

Figure 9 *Total energy discharged by battery in its lifetime with varying battery size*

5.5 Summary of energy performance

A summary of the results is given in Table 5. These results have been described in Section 4 in terms of defining an optimum performance for batteries working for RES scenarios.

From the work carried out, it is also possible to define a design table (Table 6), based on (1), showing the recommended storage sizes for given available export and for desired battery lifetimes. As (1) corresponds to, ideally, all export being displaced (or near to 100%, as defined by the plateau regions of Figs. 7 and 8), this table gives optimally sized batteries for ensuring all export is used in a given year. So, for example, if it was desired to have a battery lasting for four years, for a dwelling producing 1000 kWh of export per year, then a battery size of 12 kWh is predicted to give the optimum performance.

Table 6 should in practice be used with economic metrics. For example, again with 1000 kWh/year available export, if a 6 kWh battery was twice the price of a 3 kWh battery, there would be no obvious advantage in opting for the larger battery. However, if the 6 kWh battery was less than twice the price of the 3 kWh battery, there would now be an economic advantage in choosing the battery. The other

Table 4 Effect of different charge currents for 10.5 kWh battery with 'PV, Wind and CHP scenario'

Charge current		Discharged energy/year, kWh	Remaining export after storage/year, kWh	Predicted lifetime, years
Amps	C-rate			
25	C/10	1483	674	1.8
50	C/5	1552	532	1.7
100	C/2.5	1636	528	1.7

Table 5 Results of model calculations for battery lifetimes with RES scenarios

Technology	Total size of battery, kWh	Discharged energy/yr, kWh	Onsite generation, kWh/yr	Energy exported without battery, kWh/yr	% export captured by battery	Lifetime, years	
						Model results	Design formula
CHP	5.3	532	2340	916	83.0	2.3	1.9
	10.5	633	2340	916	98.5	3.9	3.8
	21	652	2340	916	100.0	7.4	7.6
	42	656	2340	916	100.0	14.9	15.1
	63	656	2340	916	100.0	22.4	22.7
PV	5.3	604	2594	1374	61.5	2.1	1.3
	10.5	861	2594	1374	86.7	2.9	2.5
	21	944	2594	1374	96.3	5.2	5.0
	42	983	2594	1374	99.7	10.1	10.1
	63	984	2594	1374	100.0	15.1	15.1
PV, Wind and CHP	5.3	1001	5206	2751	51.1	1.3	0.6
	10.5	1483	5206	2751	75.5	1.8	1.3
	21	1780	5206	2751	91.9	2.9	2.5
	42	1886	5206	2751	97.0	5.5	5.0
	63	1904	5206	2751	98.7	8.0	7.6

consideration is the physical size required to accommodate the batteries and associated equipment.

5.6 Economic and practical constraints on battery size

As mentioned, when looking at suitable battery sizes/configurations for a given scenario, cost and physical space of the battery will be important. Table 6 is now converted using ratios for battery costs and battery mass. The ratios used are £/kWh and Wh/kg and, therefore doubling the size of the battery will double the cost and mass, respectively. This, in practice, is not necessarily true, but is used as an approximation for Tables 7 and 8. The ratios used are 35 and 55 Wh/kg (for worst and best case energy to mass ratios) and £37 and £61 /kWh (for best and worst case cost to energy ratios) [19].

Table 6 Design table showing optimum battery sizes (kWh) for use with RES with varying lifetimes

Produced export, kWh/yr	Desired lifetime, years		
	2	4	6
500	3	6	9
1000	6	12	18
1500	9	18	27
2000	12	24	36
2500	15	30	45
3000	18	36	55

A combination of Tables 6–8 provide a designer of an RES with information for choosing an optimum battery size. For example, it might be desirable, for the case of 2000 kWh/year export, to choose a battery with a lifetime of 4 years. Tables 7 and 8 would indicate that the price of such a battery would be £889–£1482, with a mass of 441–693 kg. If this was deemed to be too expensive or too large, the user could compromise on lifetime, say opting for just a 2 year lifetime, which would then correspond to a capital cost of £445–£741 and a mass of 220–346 kg. Despite the reduced size, the RES in question should still provide approximately the same annual performance (as discussed in Sections 5.1–5.5), but would do so for 2 years instead of 4 years.

These costs do not include the extra power electronics (i.e. charge controller and inverters) that would be required if using a battery with an RES. This extra capital cost can be substantial and depends on the configuration used (see

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Table 7 Minimum/Maximum capital costs (£) of battery specifications (corresponding to battery sizes in Table 6)

Produced export, kWh/yr	Desired lifetime, years		
	2	4	6
500	111/185	222/371	334/556
1000	222/371	445/741	667/1112
1500	334/556	667/1112	1001/1668
2000	445/741	889/1482	1334/2224
2500	556/927	1112/1853	1668/2780
3000	667/1112	1334/2224	2001/3335

Table 8 Minimum/Maximum size (kg) of battery specifications (corresponding to battery sizes in Table 6)

Produced export, kWh/yr	Desired lifetime, years		
	2	4	6
500	55/87	110/173	165/260
1000	110/173	220/346	331/520
1500	165/260	331/520	496/780
2000	220/346	441/693	661/1039
2500	276/433	551/866	827/1299
3000	334/520	661/1039	992/1559

Fig. 1 for circuit adopted for battery model). Generally, the AC onsite generation (delivered to an AC bus) is converted to DC, and then passed through a charge controller, before reaching the battery. Table 7 does not include these costs and is presented as a comparison between the battery components only.

6 Conclusions

A battery lifetime algorithm is used with a previously developed lead–acid battery model to investigate the performance, and expected lifetime, of different sized batteries operating with onsite domestic generation. If a battery is to be installed with such a micro-generation system with the intention of reducing the export produced, there will exist a point where increasing battery size will not greatly improve the overall energy performance of the entire generation-with-storage system. This plateau region is estimated based on outputs of the aforementioned model. A series of design tables are produced that could be used to advise installations of electrical storage with RES, taking into account the resulting lifetime of the battery, the cost and the available annual export of the RES in question.

Based on the battery model and lifetime algorithm assumptions, the results indicate that the lifetime of a battery should increase (in a linear fashion) with battery size. However, beyond a certain point (which varies depending on the amount of available export and the battery size) the annual performance of the battery (i.e. amount of export being stored) might not improve appreciably, such that there is an optimal size of battery for any given RES. This optimum size will capture near to 100% of the available export – increasing the battery size should not increase the amount of onsite generation that is kept onsite, it would only increase the lifetime of the battery (which, beyond an acceptable lifetime limit, might be unimportant for householders, as discussed in Section 5). This is assuming that the lifetime matches the recommendations of the algorithm [17], where the battery might be replaced once the accumulated charge over time has reached a maximum 'effective' ampere-hours.

Table 6 uses this definition of optimum battery size to suggest, for given export conditions and desired lifetimes, suitable battery sizes. Using cost and weight metrics defined elsewhere, these optimum batteries are then given capital costs and physical weights. Thus, someone desiring to set up an RES with storage can use this information to choose a lead–acid battery that is a suitable compromise between energy performance, cost and physical size for a specific installation.

The results are based on actual minutely electrical demand data for a dwelling. The calculations should be repeated for other electrical demands and generation scenarios to investigate the effect import and export characteristics of different buildings have on the performance and sizing of electrical storage. For example, the micro-generation technologies chosen for this study (particularly PV and wind) are unlikely to reach maximum capacity for long periods at a time. Therefore the chances of a battery being fully charged during the charge cycle (and therefore not using all the export) are reduced. However, if a solid-oxide fuel cell CHP system is incorporated into the RES, there might be longer periods where large amounts of export (due to the high electrical efficiency of fuel-cell CHP) are available and so a larger battery would have to be used to ensure the generated power is retained onsite. These issues, along with other electrical storage options, will be incorporated in future work by the authors.

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