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Residential Battery Systems

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Section 1. IS THIS FOR ME?

Are you a TECs Members who is considering getting a residential scale battery systems? Is your household connected to the electricity grid, with an existing PV system (up to ~4kWpk) and you want to make use of surplus electricity being exported to the grid?

It also applies if you are considering a PV system and wondering whether to include a battery capability or not.

The information provided here should help you make a better, more informed, decision on whether to get such a battery system and if so what size and at what cost. It will not provide a definitive solution for your particular household as this depends how electrical energy is used (i.e. your household's behaviour).

You may only want to get a general overview of the benefits/costs of such systems, relying on expert advice to correctly dimension your specific system, if and when you decide to get one. Hopefully there is also enough technical detail if you want to dimension the system yourself or check an installer's specification/claims. The latter does need a certain level of technical understanding. TECs members can contact Dr Watt for bespoke support as part of the E-Pack programme.

As well as detailed system/usage dimensions, you can also find some rules of thumb or at least parameters (figures) to be considered/measured when deciding on a battery system.

Section 2. A GENERAL OVERVIEW

2.1 What does a residential battery system do?

There are three primary functions your residential scale battery can provide:

1. Time shifting surplus energy generated by the PV system during the day to be used when the PV system is not generating any electricity, mainly overnight.
2. Supplementing your PV generated power (or improving grid power) at peak demand to minimise energy from the grid (or overcoming fluctuating voltage or grid outages).
3. Enabling off-grid self-supply, a battery system is essential in this situation.

These functions require a battery system which is sufficiently capable/flexible to deliver this in different and changing consumption circumstances.

2.2 Why would I get a residential battery system?

As with any expenditure, there are many personal reasons why we decide to buy something. Given quite a wide range of options, the one we chose will also depend on what we are looking to achieve and the budget we have available.

The main reasons for purchasing a residential battery system tend to be:

1. Saving on electricity bills.
2. Reducing Carbon Footprint.
3. As an area of interest/investigation and/or a social statement.
4. Trading electricity.

The first of these requires that the price per unit of electricity (i.e. kWh or MWh) delivered by the battery system during its expected life is less than the unit price of electricity purchased from the grid. Basically, it requires a pay-back calculation to be made (see appendix 2).

Similarly, the second reason requires that the Carbon Footprint of the unit of electrical energy from the battery system during its lifetime incl. production and disposal is lower than that for grid electricity.

The requirements for the third reason listed above are more subjective and are limited only by the balance between the desire to do something and its affordability. This is a lifestyle choice. Nevertheless, it is worth understanding what the various parameters are in choosing the right battery system as price, functionality and efficacy can vary significantly.

More recently energy service providers have been offering electricity trading agreements, that is buying electricity at a lower price, storing this, then selling back to the grid at a higher price. Given the relatively low volumes of energy a residential system is likely to store, and the fact that margins are likely to be small, this is more of an area of personal interest. Unless someone is prepared to dedicate significant time and money, entering such arrangements is unlikely to be financially profitable.

Battery systems are of course also used for larger commercial and grid stabilisation purposes. These and other applications fall outside the scope of this paper but are covered by another TECs paper, The Future of Electricity Storage.

2.3 How much will it cost and is it worth it?

Today a good quality, medium sized Lithium-ion battery system for a typical household with an existing PV system (up to 4 kWpk) can cost ~£10,000 installed. This can vary by -50% to +100% depending on the make, size and functionality of the battery system.

Whether this is 'worth it' depends on the reasons for having it and the efficacy of the battery system, the subject of this guide. In general, at current grid prices (~£300 per MWh), it could have a break-even financial payback, provided the system has been correctly sized/specified. The simplest calculation to demonstrate this is as follows:

Assuming the PV system is delivering electricity at £0.00 (i.e. it has/will pay for itself under a separate calculation) and assuming there is sufficient capacity available from this free source of electricity (i.e. enough surplus energy to charge the battery as and when needed).

Then the unit price of the electricity delivered by the battery system = its installed price (~£10,000) ÷ its expected life (~30 MWh for a 10 kWh usable capacity of a quality battery). This comes to ~ £333 per MWh for a typical residential system, so comparable to current grid prices as these are likely to increase over the expected usable life of the battery.

Note that the typical quality battery life is likely to be longer than the usual maximum 10 year warranty period.

Even if there is a short-term energy hike in prices, in the long-term these will continue to rise at a rate greater than general inflation. As smart meters are introduced, 1/2 hourly price settlement becomes a reality and new generation comes on stream (e.g. nuclear and off-shore wind), the retail price to consumers will inevitably rise or vary in ways too complex for the average consumer to track.

Calculating the Carbon Footprint impact for a well sized battery system is given later in Appendix 2. This suggests that a relatively short Carbon payback period of less than 2 years is a realistic expectation. So, certainly a worthwhile thing to do as after this period the system will be reducing your Carbon emissions. There are, however, other ecological and social concerns associated with Li-Ion batteries.

All these ball-park calculations assume an appropriately sized battery system, the subject of the following technical details.

Section 3. THE TECHNICAL DETAILS

This section is for those members that want to specify the most appropriate battery system for their requirements. Or members that want to check that the installers' specification meets their requirements.

It is tempting to go for the largest battery we can afford, installers know this. Without a basic calculation, a battery system can easily be over or under sized, it often is.

3.1 What are the components of a residential battery system?

The main components are:

1. The battery itself, ideally with built-in Battery Management System (**BMS**).
2. A battery charging device, matched to the energy source (i.e. AC or DC source) and matched to the battery (especially if this does not have its own built-in BMS).
3. An inverter/controller to supply mains (AC) power flexibly and in accordance with pre-set rules. This should include a helpful user interface and remote management.
4. An automatic transfer switch if the system is to also function as a backup to the grid (i.e. household continues to be supplied with electricity even if the grid fails, from PV and battery).

Each of these components will need to be specified to be operationally and price optimised to the residential property and its occupants. The key parameters for each component will be explained later. Normally these are specified by the installer, but not all installers have the same level of expertise or interest in optimising a battery system. In fact, most installers provide a standard solution irrespective of user requirements.

3.2 Measure the existing electrical systems before considering a battery system

In order to achieve the best match (i.e. efficacy of the battery system for the users), avoiding unnecessary cost and likely disappointment, a number of measurements are essential:

1. The current electricity consumption (in kWh), ideally daily, monthly or at least the seasonal variations. Where there are smart meters fitted, the data from these should be used (normally available from the electricity provider). Note that this should include consumption from sources other than the grid (e.g. a PV system).

2. The household's Base-Load, i.e. the power consumed at night when no one is 'active'.

3. The typical peak power (with seasonal variation if applicable), i.e. what appliances are likely to be on together and how often this occurs.

4. If there is an existing alternative source of electrical energy (e.g. PV), what is this, what is its typical energy output and how much of this energy is used on site/exported to the grid. Ideally these figures should be available daily or monthly/quarterly to establish seasonal variation.

5. It will also be useful to understand the household's past/future electricity consumption, is it likely to increase/reduce in the future and by how much? Is there a measured track record which confirms this? It is particularly important to know the consumption of high energy devices such

as heat pumps, electric vehicles, cooking, refrigeration, etc.

6. The unit prices (for all sources of existing electricity, i.e. including any PV system) is necessary, especially if price/budget is an important consideration.

Appendix 1 gives actual examples of the measurements (figures) above, while appendix 2 explains how to use today's prices for your home.

Providing this information to a knowledgeable installer should help them size and configure the system correctly. TECs Members can use the Dr Watt service to help with both obtaining these figures and advising on system configuration.

3.3 How to specify the battery

Only Lithium-ion batteries should be considered as their price/performance and Carbon Footprint are ~4x better than Lead-Acid versions. Since these batteries will need to make financial/carbon sense (i.e. make a positive contribution beyond their initial financial/carbon cost), they will typically need to last at least 10 years and therefore be backed by a reputable/enforceable warranty.

Battery technology is changing rapidly, this could be the materials used in building it, the controls available to manage the flow of electricity or the longevity and safety of the battery itself. Some of these may be used to simply market the product while others are genuine features worth having. Do your own research or ask Dr Watt if you are unsure.

Most reputable batteries intended for a grid-connected household will have a built-in BMS. Note that only if the system is not connected to the electricity grid (e.g. off-grid application) can the charging of the battery be controlled through an external battery charger which would need to be configured to double-up as the BMS.

There are several key parameters to consider:

1. The storage capacity (in kWh), this is dimensioned to supply the daily time-shifted energy needed. Typically, the battery capacity should be large enough to deliver all the energy needed when the sun is at its weakest during the winter season, so:
   Capacity = Base-Load x 14hrs + additional evening electricity usage (e.g. cooking, TV, lighting)
   This is a good starting point. Having detailed consumption profiles will make this calculation much easier and more accurate. See appendix 2 for example calculations.

2. Additionally, the surplus energy (i.e. that currently exported to the grid) will limit the size of the storage capacity. It may not be cost effective to oversize the storage capacity if insufficient surplus energy is available from the PV system. This is the case when PV generation is mostly consumed during the day, so not available to charge the battery.
   Batteries come in specific capacity sizes, but can be 'paralleled' to increase storage capacity.
   They should also not be fully discharged, so at least 10% of the stated capacity is unavailable.
   Limiting the depth of discharge will have an impact on the expected life of the battery, this data should be available from the manufacturer's literature.

3. The maximum/standard discharge rates, these are given in kW and are typically in a 2:1 ratio to achieve the maximum battery life expectancy. Although this should be chosen to be close to the typical maximum peak power usage in the winter, many households will exceed this demand significantly. Typically 3-5kW is recommended as this figure is also linked to the size (and

therefore cost) of the inverter/controller component of the system.
This is also the figure which can be added to the power generated by an existing PV system to supplement any peak demand during the day.

4. The life of a battery is normally given in maximum full discharge cycles until it reaches a Depth of Discharge (**DoD**) limit for useful operation. Note that partial discharges are added together. Alternatively, this is given in total energy delivered (in MWh) which is equivalent to the battery storage capacity (in KWh) X max. no. full discharge cycles. Typically, a correctly sized system will discharge about 150-250 times annually. Max full discharges for the specified conditions are 2,000 - 8,000 cycles, so a 10 year battery life span should be expected and is often quoted for a quality product. It is essential to adhere to the specified conditions to ensure any warranties are not disputed (inverter/controllers keep long term records for verification).

5. Although battery efficiency (ratio of energy-in to energy-out) is an important factor, it is not the most important figure. While a battery may claim an efficiency of ~90%, a typically system efficiency ranges between 60-80% and is dependent on charger, inverter/controller, temperatures, charge/discharge cycle frequency and power rates.
The efficiency is important in calculating the relationship between the battery capacity and the PV system energy available to recharge the battery. This ultimately defines the likely number of full discharge cycles, essential for pay-back calculations.

3.4 How to specify the battery charger

For grid connected systems, and those with battery-backup functionality, the battery charger is typically integrated into the inverter/controller component. More recently, much has been made of AC vs. DC coupled battery systems. A DC-coupled battery is charged direct from the PV panels, so is more efficient than one where the DV from the PV panels is first converted to AC, then back to DC to charge the battery. While there are efficiency gains, the choice will be more dependent on what functionality/flexibility is required, what limitations there may be especially where an existing system is being upgraded, and the manufacturer's preference. If you need help with these options, please contact Dr Watt.

For certain configurations (e.g. off-grid systems), this can be a DC-DC converter (i.e. a DC-coupled battery charger) and should be sized/configured to manage the battery manufacturer's specifications. The charger should also be matched to, or ideally supplied by, the same manufacturer as that of the inverter component used.

Most installers will be aware of the guidance for grid connection with battery systems. There are some differences on how maximum installed capacity is determined, but often this can be negotiated if other forms of export control are installed. Please ask Dr Watt if you have such concerns with designing your system.

3.5 How to specify the inverter/controller

The main parameter for sizing this component is the maximum power required (in kW). This will depend on the sizing of the battery itself and should be set just above the maximum required for the household. The battery charge/discharge rate can be set below this and must not exceed the battery's warranty conditions.

There are now several manufacturers on the market, some integrate this component with other battery component which should make warranty issues easier to address. The user interface, remote control, flexibility in programming/configuration and warranties will be the significant criteria for choosing the make and model.

The other important parameter is whether a single or multiple inverters are used, see also section 3.4. This can save on costs but may limit functionality, please ask Dr Watt if you need help with your specific installation design.

Although not necessary, it is advisable to use the same manufacturer for battery chargers/inverters/controllers. This will make interoperability and management of these a lot easier.

3.6 How to specify a transfer switch

If this component is required (e.g. to keep the building supplied and the PV operational when the grid has failed), its size will be determined by the grid connection capacity and compatibility with the inverter/controller component.

Some battery systems integrate this functionality with the other battery components.

Most PV systems use grid-tied inverters, so if the grid fails or exceeds the conditions set by the Distribution Network Operator (e.g. voltage, frequency, number of outages, Loss of Mains, etc.), the PV system will not operate. While it is possible to continue using the PV system's energy where there is another source of 'regulated' electricity (e.g. a battery system), this is only legally permitted when a certified transfer switch to isolate the grid is also installed.

The typical price of a G59/3-7 compliant switch is ~£2,000, this is likely to make a financial pay-back even more challenging unless grid electricity prices start to rise significantly.

While we still have a reliable electricity grid and there are no other reasons for having this functionality, it is not necessary to have this component for most homes.

3.7 Physical size and location of a battery system

Most of the sizing for the individual components has been explained above. Appendix 2 has some further practical numbers from installed systems.

The physical size of a battery system can be relatively large (1.5m x 1m x 0.5m). This and the fact that these systems will generate some noise when working (e.g. cooling fans and switching relays) will limit where they can be installed. The battery also operates optimally at ~15^{o}C , so locating these outdoors is not ideal unless the area is adequately temperature controlled.

Section 4. Appendix 1- Example measurements

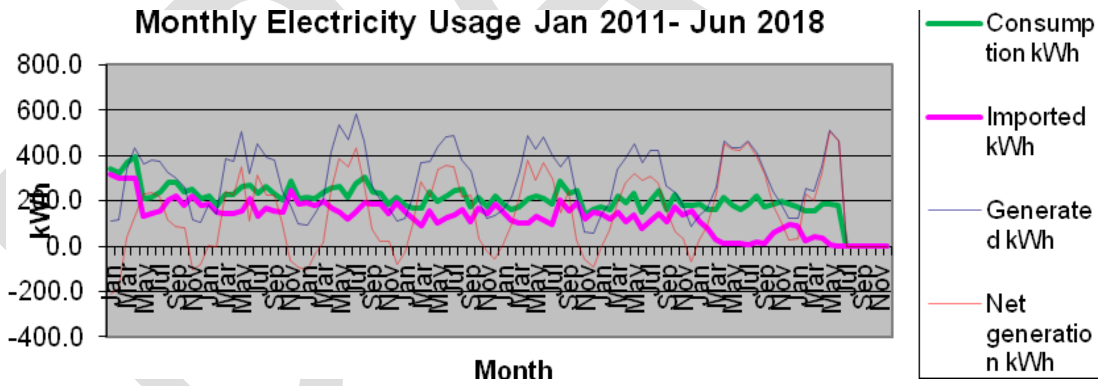
The following are example figures measured for two actual residential PV systems. Neither example initially had a battery system.

4.1 Example 1: small house, modest consumption (2018 prices)

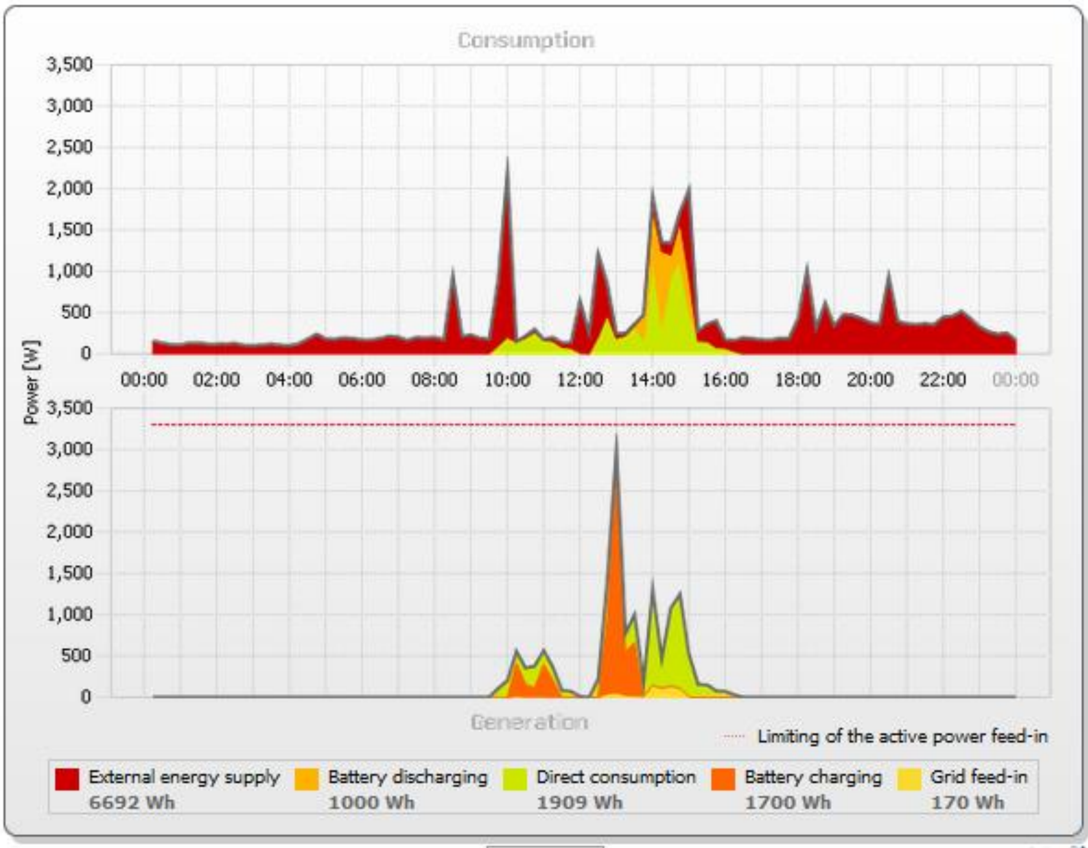
1. Annual electricity from grid ~ 0.8 MWh @ £146.4 per MWh + £80 annual charges
   Monthly electricity consumption (from grid & PV)= 200 kWh +/- 50 kWh winter/summer variation, so an average daily consumption of ~6 kWh
2. Base-Load = 200 W
3. The typical peak power = ~3 kW
4. PV system = 2.07 kWpk ; annual generation = ~1.75 MWh ; monthly average ~145kWh ranging between 50-200 kWh per month

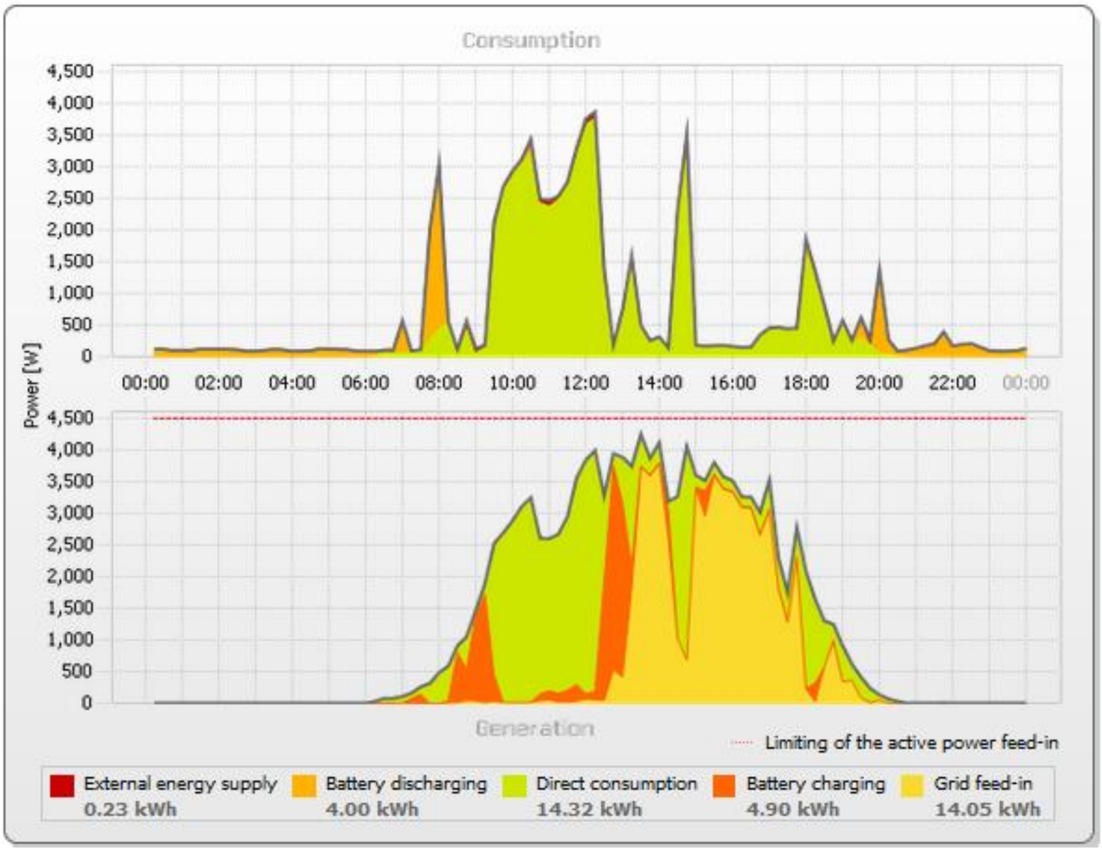
4.2 Example 2: large house, modest consumption (2018 prices)

1. Annual electricity from grid ~ 1.6 MWh @ £146.4 per MWh + £84 annual charges
   Monthly electricity consumption (from grid & PV)= 180 kWh +/- 30 kWh winter/summer/visitors variation, so an average daily consumption of ~6 kWh
2. Base-Load = 100 W ; 200 W with visitors
3. The typical peak power = ~4 kW during cooking
4. PV system = 3.78 kWpk ; annual generation = ~3.65 MWh ; monthly average ~300kWh ranging between 50-500 kWh per month ; average monthly export ~80%
5. Chart below starts 2011 with a 3.2 kWpk PV system ; Battery system was installed in Jan 2017



The following are typical winter (January) and summer (July) daily consumption patterns for this installation, both include some electric vehicle charging in 2022.





Section 5. Appendix 2- Example calculations

In general, the payback calculation is:

Payback time = (price of new system) / (annual cost of old system– annual cost of new system)

similarly for Carbon = (Embedded Carbon to manufacture system) / (current annual CO_2e emissions – new annual CO_2e emissions)

To save money or Carbon, the payback time must be longer than the expected life of the system, otherwise the two most common reasons for installing a battery system are not achieved.

The following calculations use the calculations suggested in this document to establish how close a battery systems can be in at least breaking even. Annual costs whether £ or kg of CO_2e can be a bit tricky to work out, so you may need to replace the figures used here with ones that are applicable to you at the time. As grid electricity gets decarbonised and energy price inflation accelerates (as has happened in 2022), the figures will have a significant impact. If you are unsure what figures apply, you can use the E-Pack to find out or contact Dr Watt for advice.

Please note that these are very rough calculations based on limited information. They do not take account of your daily consumption patterns or the daily variation in PV generation. These patterns can be obtained from your Half Hourly meter readings and expected/actual PV generation readings for your building/system.

5.1 Worked example of a typical house with low consumption

Average daily consumption of 6kWh; Base Load of 100W (assumes largely unchanged electricity consumption throughout the year); Overnight winter consumption excluding Base Load is 3.4 kWh; daytime winter consumption is 20% of total; daytime summer consumption is 57% of total.

Battery capacity to cover daily winter usage overnight = 100W x 14 hrs + 3.4 kWh = 4.8 kWh

Or another way of doing this calculation depending on the

Battery capacity to cover daily winter usage overnight = 6 kWh x 80% = 4.8 kWh

For a well-positioned 4kW PV system, ~6 kWh average daily generation in the winter is possible. Assuming 20% is used during the day, and allowing for ~30% extra to cover battery system losses, leaves 6kWh x 80% x 70% charge in the battery = 3.36 kWh for overnight use.

The battery system suggested: 6 kWh battery capacity would supply overnight consumption for ~half the overnight winter demand (the sun doesn't always shine!); 3kW nominal battery and inverter/controller power (this is the maximum power the battery system can supply); typical average monthly cycles ~15 (180 p.a.), so for a 10 year warranty the battery system can deliver approximately:

6 kWh x 180 cycles X 10 years = 10.8 MWh of 'avoided' energy from the grid.

Or another way of calculating this if the figures are available:

120 days x 3.36 kWh (winter average) + 245 days x (6 x 0.43) kWh (summer average) = 1.04 MWh/year
Less overnight energy is needed from the battery in the summer because the nights are shorter, the PV system can supply 100% of the summer overnight demand.

Based on the payback formula, the 'avoided' energy use from the grid (i.e. the difference between old & new battery system) would approximately be:

£ payback time = (£6,000 installed price of battery system) ÷ ((1.04 MWh/year saving expected with battery system) X £300 per MWh) = ~19 years

A 4 kWh battery system may be adequate if overnight consumption remained the same as above. At ~£4,000 it would have a payback period of ~13 years.

While a 10 kWh battery system at £10,000 for the same conditions would have a ~32 year payback!

Quality battery systems are expected to last more than ~10 years, often delivering 3,000 cycles before the battery becomes inefficient. That is equivalent to almost doubling the warranty life of this system to ~20 years. Also, future increase in grid unit price will shorten the payback duration by ~1 year, equivalent to a saving of ~10% or £42 over 10 years.

It should also be noted that the battery system will also be used during the day as the PV system generation will vary with sunshine intensity, cloud cover, shading. This will increase the potential 'avoided' energy imported from the grid, but not by an appreciable amount. In the calculation above this is highlighted as 1.08 MWh/year vs. 1.04 MWh/year difference using different calculation methods, the former includes an estimate of the daytime battery usage.

Carbon payback time = 400 kg CO_2e (based on ~8 kg CO_2e per kg of battery system materials) ÷ 1.04MWh/year x 250 kg CO_2e per MWh (grid electricity Carbon Intensity) = ~ 1.5 years

Or using an alternative reference for embedded emissions

Carbon payback time = 75 X 6 kWh (based on ~75 kg CO_2e per kWh of storage capacity) ÷ 1.04MWh/year x 250 kg CO_2e per MWh (grid electricity Carbon Intensity) = ~ 1.7 years

The Carbon payback time uses a simple approximation of embedded Carbon based on materials, this may vary significantly between countries of origin for the materials/manufacture, but is a reasonable indicator (See the TECs E-Pack for references). Since the embedded Carbon in creating the grid that makes and delivers our electricity has not been included in the calculation, the assumption on embedded Carbon for the battery system is considered to be more than reasonable.

As the electricity grid decarbonises, the Carbon payback period will increase. However, it will always be well within the expected life of the system, provided the embedded emissions are as suggested by this calculation.

5.2 Worked example of a typical house with high consumption

Average winter daily consumption of 20kWh (e.g. heating with a heat pump) and 10kWh daily summer consumption; Base Load of 200W (assumes significant electricity consumption variation throughout the year); Overnight winter consumption excluding Base Load is 8 kWh; daytime winter consumption is 40% of total; daytime summer consumption is 80% of total.

Battery capacity to cover daily winter usage overnight = 200W x 14 hrs + 12 kWh = 14.8 kWh

Or another way of doing this calculation depending on the

Battery capacity to cover daily winter usage overnight = 20 kWh x 80% = 16 kWh

For a well-positioned 4kW PV system, ~6 kWh average daily generation in the winter is possible. Assuming 40% is used during the day, and allowing for ~30% extra to cover battery system losses, leaves 6kWh x 60% x 70% charge in the battery = 1.44 kWh for overnight use.

The battery system suggested: 4 kWh battery capacity would supply overnight consumption for ~10% overnight winter demand (the sun doesn't always shine!); 3kW nominal battery and inverter/controller power (this is the maximum power the battery system can supply); likely average monthly cycles ~5 (60 p.a.), so for a 10 year warranty the battery system can deliver approximately (note that this battery is underutilised hence the low annual cycles):

(20+10)/2 kWh x 60 cycles X 10 years = 9 MWh of 'avoided' energy from the grid.

Or another way of calculating this if the figures are available:

120 days x 1.44 kWh (winter average) + 245 days x (10 x 0.2) kWh (summer average) = 0.663 MWh/year
Although less overnight energy is needed from the battery in the summer because the nights are shorter, there is more PV generation available in the summer to cover 100% of the overnight demand.

Based on the payback formula, the 'avoided' energy use from the grid (i.e. the difference between old & new battery system) would approximately be:

£ payback time = (£4,000 installed price of battery system) ÷ ((0.663 MWh/year saving expected with battery system) X £300 per MWh) = ~20 years

A 2 kWh battery system may be adequate if overnight consumption remained the same as above. At ~£2,500 it would have a payback period of ~12 years.

While a 6 kWh battery system at £6,000 for the same conditions would have a ~30 year payback!

Quality battery systems are expected to last more than ~10 years, often delivering 3,000 cycles before the battery becomes inefficient. That is equivalent to almost tripling the warranty life of this system to ~30 years. Also, future increase in grid unit price will shorten the payback duration by ~1 year, equivalent to a saving of ~10% or £42 over 10 years.

It should also be noted that the battery system will also be used during the day as the PV system generation will vary with sunshine intensity, cloud cover, shading. This will increase the potential 'avoided' energy imported from the grid, but not by an appreciable amount. In the calculation above this is highlighted as 0.9 MWh/year vs. 0.663 MWh/year difference using different calculation methods, the former includes an estimate of the daytime battery usage.

Carbon payback time = 300 kg CO_2e (based on ~8 kg CO_2e per kg of battery system materials) ÷ 0.663MWh/year x 250 kg CO_2e per MWh (grid electricity Carbon Intensity) = ~ 1.8 years

Or using an alternative reference for embedded emissions

Carbon payback time = 75 X 4 kWh (based on ~75 kg CO_2e per kWh of storage capacity) ÷ 0.663MWh/year x 250 kg CO_2e per MWh (grid electricity Carbon Intensity) = ~ 1.8 years

The Carbon payback time uses a simple approximation of embedded Carbon based on materials, this may vary significantly between countries of origin for the materials/manufacture, but is a reasonable indicator (See the TECs E-Pack for references). Since the embedded Carbon in creating the grid that makes and delivers our electricity has not been included in the calculation, the assumption on embedded Carbon for the battery system is considered to be more than reasonable.

As the electricity grid decarbonises, the Carbon payback period will increase. However, it will always be well within the expected life of the system, provided the embedded emissions are as suggested by this calculation.