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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 system? Is your household connected to the electricity grid, with an existing PV system (up to ~4kWpk) and you want to make use of surplus (excess) 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. Understanding how to specify a battery system 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 (numbers) 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.
4. Storage of electricity bought at off-peak rates for later use during peak rate periods.

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

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 our Carbon Footprint.
3. As an area of interest/investigation and/or a social statement.
5. Benefiting financially from different grid electricity tariffs.

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). For most 'typical' households, the payback is likely to be longer than the warranty period. It is almost always better to assume that there will be no financial benefit from having a battery system. Even when there is a financial return, this will be marginal.

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. This is also referred to as "Emission Factor" or "Carbon Intensity" (**CI**). Here the carbon payback is likely to be positive for most well designed/dimensioned systems when charged from surplus PV generation.

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 amount of energy a residential system is likely to store from the grid, and that the electricity CI will increase, we do not recommend charging batteries from the grid. Please refer to the on-line calculator to work out your personal circumstances.

Unless someone is prepared to dedicate time and money, entering such arrangements, it is unlikely to be financially profitable. It should be noted that most of these tariff arrangements will inevitably be temporary. They tend to benefit the retail provider, either to encourage/discourage usage at certain times or as a marketing tool.

Please also refer to TECs' paper on Greenwash, for more information on low-carbon electricity claims.

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 (usually up to 4 kWpk) can cost £3,000 to 15,000 installed. This will depend on the make, size and functionality of the battery system. VAT has recently been removed from residential battery systems.

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 a grid price of ~£300 per MWh (i.e. 30 pence per kWh), it could have a break-even financial payback, provided the system has been correctly sized/specified and the battery usage is high, at least 50% utilisation. 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. provided there is enough surplus energy to charge the battery as and when needed).

The unit price of the electricity delivered by the battery system =
its installed price (~£10,000) ÷ its expected life (e.g. ~30 MWh for a 10 kWh usable capacity of a quality battery).

This comes to ~ £333 per MWh if the battery is 100% utilised, so close to a grid price of £300 per MWh. That means it just about breaks even financially if grid prices did not change over the next 10 years. However, as prices are likely to increase over the expected usable life of the battery, it is likely to represent a financial pay-back. How much depends on the level of increase in electricity prices over that period.

Even if there is only a short-term energy hike in prices, in the long-term these will very likely 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 electricity generation comes on stream (e.g. nuclear and offshore wind), the retail price to consumers will inevitably rise or vary in ways too complex for the average consumer to track.

On the other hand, a typical household will struggle to utilise the battery to 100%. The higher the utilisation the faster the payback. However, higher utilisation also reduces the life of the battery, please refer to the detailed section for more information on this.

Note that the typical quality battery life is likely to be longer than the usual maximum 10 year warranty period quoted, albeit at a much reduced level of energy it can store. Every charging cycle reduces the storage capacity of the battery.

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 ~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 the manufacture and disposal of Li-Ion batteries. Please refer to Section 4.

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. It is also for 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, Li-Ion batteries are normally supplied with a built-in Battery Management System (**BMS**).
2. A battery charging device, matched to the energy source (i.e. AC or DC source) and appropriate for the battery.
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 first 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 using theoretical examples.

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 Broader system considerations

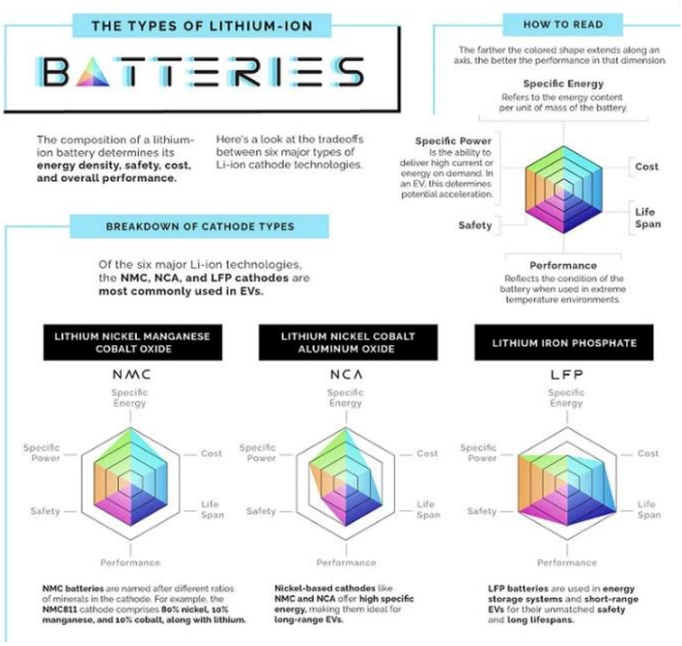
Apart from considering each of the main components of the system, you should also consider other general and longer-term aspects. It is useful to do this as battery storage systems represent a significant investment that lasts at least 10 years.

1. Our lives are decarbonising, that means electrification of heating and transport. This is likely to result in:
    a. Additional electrical loads such as Electric Vehicles (**EV**), heat pumps, electric induction cookers, air conditioning units.
    b. Installation of additional PV to deal with additional loads.
    c. It is the government's policy to decarbonise grid electricity, by how much and by when is not yet clear.
2. The electricity market is likely to change in the next few years, so flexibility could be important. Half Hourly (**HH**) based tariffs will become more widely used to encourage us to shift behaviour in terms of when and how much grid electricity we consume.
3. How battery systems are considered by the regulator is changing. Check with Western Power Distribution (**WPD**) to make sure you are fully compliant with their current, and likely future grid connection requirements, especially when extending an existing system. You are likely to need some expert advice on this, so ask your installer to check or contact Dr Watt.
4. You should consider the extent to which you want to control/monitor the system. Most manufacturers provide web-based apps for this which you can read about. Some also provide an Application User Interface (**API**) to allow you or a separate commercial organisation to write a different/bespoke app. This is a specialised area for those who want to determine their own control/monitoring functionality. It may also prove useful for members wanting to have direct control to benefit from any HH tariff arrangements.

3.4 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. Please refer to the following links to find out more about the differences between the various battery technologies:

- [Electronics360 short article](#) (picture shown here)
- [Academic life cycle assessment](#)



The composition of a lithium-ion battery determines its **energy density, safety, cost, and overall performance.**

Here's a look at the tradeoffs between six major types of Li-ion cathode technologies.

The farther the colored shape extends along an axis, the better the performance in that dimension.

Specific Energy Refers to the energy content per unit of mass of the battery.

Specific Power Is the ability to deliver high current or energy on demand. In an EV, this determines potential acceleration.

Performance Reflects the condition of the battery when used in extreme temperature environments.

Of the six major Li-ion technologies, the **NMC, NCA, and LFP cathodes** are **most commonly used in EVs.**

NMC batteries are named after different ratios of minerals in the cathode. For example, the **NMC811** cathode comprises **80% nickel, 10% manganese, and 10% cobalt, along with lithium.**

Nickel-based cathodes like **NMC and NCA** offer **high specific energy,** making them ideal for **long-range EVs.**

LFP batteries are used in **energy storage systems** and **short-range EVs** for their unmatched **safety** and **long lifespans.**

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 considering. Do your own research or ask Dr Watt if you are unsure.

There are several key parameters to consider, in order of importance:

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 (daily) 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 (i.e. max is twice the standard discharge). Although this should be chosen to be close to the typical maximum peak power usage in the winter, many households will periodically 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 a DOD of 50-60%, 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).

   Note that manufacturers sometimes specify life-time cycles for a DOD less than 50% or don't give a DOD specification. These manufacturers should be avoided.
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%, in practice a typical system efficiency ranges between 60-80% and is dependent on charger, inverter/controller, temperatures, charge/discharge cycle frequency and power rates. Only a few control systems or

manufacturer’s data sheets give efficiency figures that include all losses associated with charging/discharging a battery.
The efficiency is, however, 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. If in doubt use an efficiency of 75% for batteries from a ‘reputable’ manufacturer.

3.5 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 DC electricity from the PV panels is first converted to AC, then back to DC to charge the battery. For AC-coupled systems a typical efficiency of 75% can be expected.

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.

3.6 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 (see section 3.5 parameter #2) and should be set just above the maximum required for the household’s high consumption rates (e.g. using an electric kettle or oven). The battery charge/discharge rate can be set below this as it must not exceed the battery's warranty conditions.

There are now several manufacturers on the market, some integrate these components with other battery components 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 single or multiple inverters are used, see also section 3.5. 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 as well as PV system inverter/controller. This will make interoperability and management of the overall PV/battery system a lot easier. Several manufacturers are now also offering their own battery packs, sometimes these are rebranded.

3.7 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.

3.8 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°C , so locating these outdoors is not ideal unless the area is adequately temperature controlled.

3.9 Full DIY Approach

It is possible to make considerable savings by buying the components separately and getting them installed by a qualified electrician. The components required are readily advertised online by various solar industry wholesalers and equipment manufacturers.

The battery itself is the most expensive component. The cheapest approach is to build a battery from LifePo4 cells, which are 3.2V cells that you connect in series to make a nominal 12, 24 or 48Volt battery, this requires significant electrical/electronic competence. Here you would also need to build the box to hold the battery and fit a battery BMS to monitor the voltage of each cell, finding a good one can be difficult. There are plenty of videos on YouTube which describe this approach in more detail.

Alternatively, modular batteries are also available they can be plugged together in parallel and stacked. These include all connectors and a BMS. Modules need to be connected to a management system via an RS485 or CAN bus. The management system is typically provided by an inverter charger, you'll need to ensure interoperability if you are buying an off-the-shelf management/control system.

Theoretically you could put a modest size system together for as little as £2,500 using commercial modular batteries and inverter/controller. Installation should not be any more complex than other systems and should be within the capabilities of a qualified electrician, if they are prepared to do this under your supervision and with you taking full responsibility. Success is likely to depend on the level of support available from the documentation supplied. Choosing manufacturers with a large worldwide installed base may be worth paying extra for to get clear instructions in English. Telephone support is normally limited to registered installers.

Important things to consider:

- If the system is grid connected the DNO will need to be give permission for the connection and will certainly need to be notified, this is no different from other batteries and control systems, except that notification is normally done by the supplier. It would now be your responsibility and likely to need type approval, so is beyond most DIY projects!
- Warranties for components will be separate and be dependent on the manufacturer's longevity, reputation and insurance cover.
- You will be responsible for ongoing support and maintenance.

Section 4. Ecological Impact

There are differences in terms of environmental and climate impacts of the different Lithium-Ion technologies. These are more complex to assess especially with some of the recent claims from manufacturers and environmentalist. There are several academic studies of these life cycle impacts, e.g. here.

Specifically, the mining of some of the precious metals can have significant detrimental ecological, as well as geo-political and social impacts. It is therefore important to find out where/how these batteries are made, recycled and disposed of. Examples of more balances and readable sources can be found here:

- Lithium-ion batteries need to be greener and more ethical (Nature)
- Environmental impacts of lithium-ion batteries (UL research)
- Environmental impacts of lithium-ion batteries (AZ of Clean Tech)

Section 5. Appendix 1- Example measurements

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

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

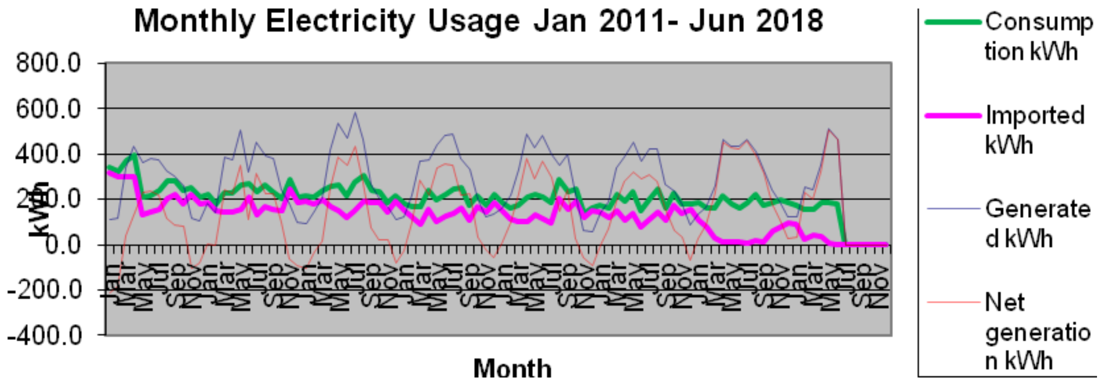
1. Annual electricity from grid ~ 0.8 MWh @ £146.4 per MWh + £80 annual charges
   - Monthly electricity consumption (from grid & PV)= 200 kWh +/- 50 kWh winter/summer variation, so an average daily consumption of ~6 kWh
2. Base-Load = 200 W
3. The typical peak power = ~3 kW
4. PV system = 2.07 kWpk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

In this case the installer recommended a 2 kWh battery system but replaced the original PV inverter with an integrated battery and PV inverter. The user was not aware of either the functionality they were getting or the likely financial/carbon savings.

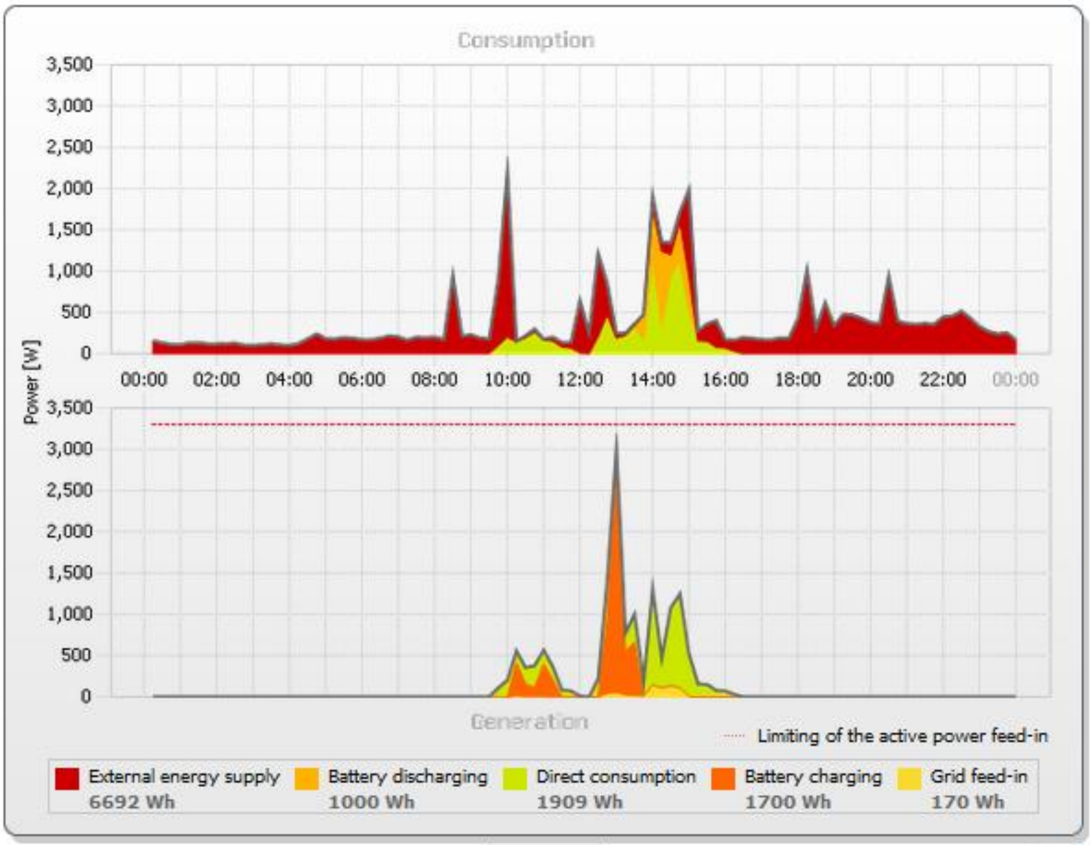
5.2 Example 2: large house, modest consumption (2018 prices)

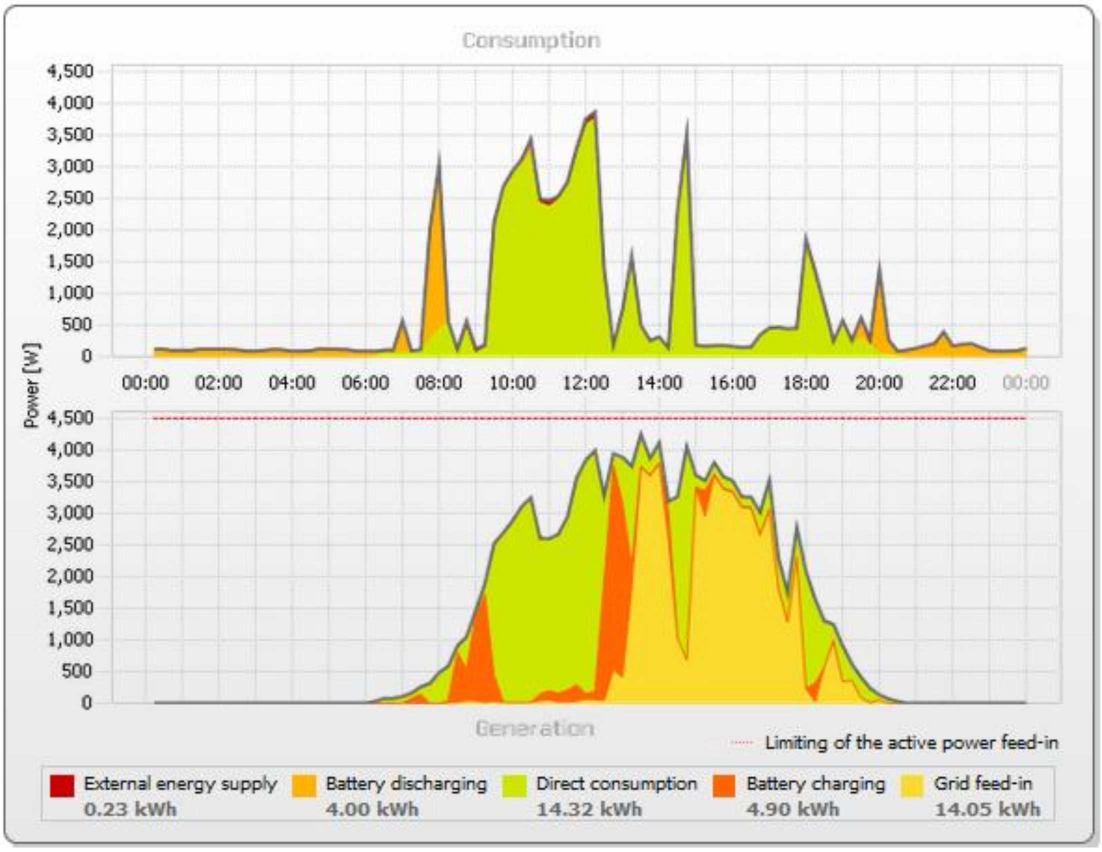
1. Annual electricity from grid ~ 1.6 MWh @ £146.4 per MWh + £84 annual charges
   - Monthly electricity consumption (from grid & PV)= 180 kWh +/- 30 kWh winter/summer/visitors variation, so an average daily consumption of ~6 kWh
2. Base-Load = 100 W ; 200 W with visitors
3. The typical peak power = ~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

In this case the owner worked with the installer to specify a 6kWh battery system with off-grid capability. At the time the user was aware that this system would not pay back during the warranty period, but would represent a significant emissions reduction (~1 t CO2e annual avoided emissions). With the 2022 doubling of energy prices the system will now pay for itself within the warranty period.



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





Section 6. 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 shorter 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. If included, they will increase the battery use/cycles in line with how much daytime electricity you consume (typically 10-20% additional battery capacity). Instead of winter/summer averages, you can do the same calculations using your daily/Half Hourly meter readings and expected/actual PV generation readings for your building/system.

Use the calculations below for your own circumstances by replacing the various parameters with measurements/data applicable to you and the systems you have or intend to get. You can add large loads (e.g. electric vehicle ~10kWh daily all year round or heat pump ~30kWh on winter days). Batteries will be ineffective during the winter for heating with electricity (e.g. heat pumps or night storage) because there is very little surplus PV generation.

6.1 Worked example of a typical house with low consumption

This example is for a largely unchanged electricity consumption throughout the year. The battery is dimensioned to bridge one typical day/night in the winter before needing to be recharged.

- Base Load ($\mathbf{Bas_l}$) = 100W;
- Average 24hr consumption, winter ($\mathbf{Con_{dw}}$) = 6kWh;
- Average 24hr consumption, summer ($\mathbf{Con_{ds}}$) = 6kWh;
- Average night-time winter consumption excl. Bas_l ($\mathbf{Con_{nw}}$)= 4.2 kWh
- Average night-time summer consumption excl. Bas_l ($\mathbf{Con_{ns}}$)= 3 kWh
- Average winter hours ($\mathbf{Hrs_w}$) = 14 h
- Average winter hours ($\mathbf{Hrs_s}$) = 6 h

overnight consumption for a typical winter = Bas_l x Hrs_w + Con_{nw}

= 100W x 14 hrs + 4.2 = **4.6 kWh** << this is the minimum battery capacity to meet overnight demand

For the summer overnight consumption equivalent = Bas_l x Hrs_s + Con_{ns}

= 100W x 6 hrs + 3 = **3.6 kWh** << this is almost always less than the winter demand

For a well-positioned 4kW PV system

- Average 24hr generation, winter (**Gen_{dw}**) = 5 kWh;
- Average 24hr generation, summer (**Gen_{ds}**) = 25 kWh;
- Typical efficiencies incl. charging/discharging/other losses (**Bef**) = 75%

Surplus PV generation available in the winter = $\text{Gen}_{dw} – (\text{Con}_{dw} – \text{Con}_{nw})$

= 5 kWh – (6 kWh – 4.2 kWh) = 3.2 kWh

Available after storage inefficiencies = $(\text{Gen}_{dw} – (\text{Con}_{dw} – \text{Con}_{nw})) \times \text{Bef}$

= 3.2 x 0.75 = **2.5 kWh** << this is the maximum battery capacity needed to maximise cost efficacy

The same calculation can be done for the summer surplus = $(\text{Gen}_{ds} – (\text{Con}_{ds} – \text{Con}_{ns})) \times \text{Bef}$

=25 kWh – (6 kWh – 3 kWh)) x 0.75) = 22.5 kWh << this will almost always be greater than the winter surplus

The size of the battery chosen will be a compromise between these two calculations. That is how much overnight consumption is to be supplied and how much surplus PV generation is available. The calculation gives you a range rather than an optimal capacity for all your criteria. The decision will ultimately depend on what you are trying to achieve.

To illustrate this theoretical example we've assumed batteries come in 2, 4, 6, 10 kWh capacities. In practice they typically come in 2.4 kWh increments, so 2.4, 4.8, 7.2, 9.6 kWh etc. There will be exceptions to these, and remember to check the usable capacity as opposed to the maximum.

For the example here, a 4 kWh battery would be more than adequate to maximise the cost efficacy of the system. It may not quite achieve the overnight storage requirement, but it will have additional capacity to store/use surplus PV energy in the summer

Your choice may also be influenced by the maximum load you want the battery to supply. A 4 kWh battery would typically deliver 2kW while a 6 kWh battery delivers 3kW peak power. You may also want to consider future changes in your electricity demand. The consequence of your choice of battery capacity will have an impact on the pay-back period, especially the financial one. Here is the calculation for this example:

- Winter days (**Day_{w}**) = 120 d
- Summer days (**Day_{s}**) = 245 d
- Manufacturer's warranty for a DoD of 60% (**C_{dod}**) = 3,000 cycles or 10 years

Annual surplus PV electricity cycled through the battery (from first box above)
= winter demand x Day_{w} + summer demand x Day_{s}

= 4.6 kWh x 120 d + 3.6 kWh x 245 d = **1.434** MWh/year << this is the avoided grid electricity

To make sure the battery does not exceed its warranty (4kWh usable capacity)

4kWh x **C_{dod}** should be > 1.434 MWh/y x 10 y

12 MWh is not > 14.34 MWh << the usage will exceed the warranty

Although the battery usage exceeds the warranty, it is not by much. The battery will continue to operate but at lower capacity, ~60% capacity after 10 years.

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) ÷ ((1.434 MWh/year saving expected with battery system) X £300 per MWh price of grid electricity) = ~**9.3 years**

If you had chosen a 6 or 10 kWh battery system, the payback would have respectively been

= £6,000 ÷ (1.434 x 300) £/y = 14 year pay back

= £10,000 ÷ (1.434 x 300) £/y = 23 year pay back

Quality battery systems are expected to last more than ~10 years although at a reduced performance. Quality batteries outperform their warranty period, sometimes doubling this. Also, future increase in grid unit price will shorten the payback duration by ~1 year, equivalent to a saving of ~10% or £430 over 10 years.

Using the same calculation for Carbon payback time =

350 kg CO_2e (based on ~8 kg CO_2e per kg of battery system materials) ÷ 1.423MWh/year x 250 kg CO_2e per MWh (grid electricity Carbon Intensity) = **~ 1 year**

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) ÷ 1.434MWh/year x 250 kg CO_2e per MWh (grid electricity Carbon Intensity) = ~ 10 months

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 can be considered to be 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.

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. Only a much more detailed analysis of daily or even half hourly consumption/generation data would be required. This is beyond the scope of this guide, but if you want to know how this can be done, please ask Dr Watt.