Domestic Energy Solutions Primer

Energy Storage

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Contents

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Introduction

There are two types of energy storage – electrical and thermal.

Electrical storage stores electricity using a battery. On an industrial scale there are systems based on pressured fluids (air or water) and vacuum-enclosed flywheels that use electrical generators to release the energy, but for normal building use only battery-based systems are currently practical.

Thermal storage stores heat by raising the temperature of a substance or changing the phase of a substance. Heat energy is recovered by cooling the substance and transferring the stored energy to another system. As the energy is stored and released as heat, this restricts the store usage to heat-based applications (e.g. Space Heating, Domestic Hot Water (DHW).

The key differences between electrical and thermal storage are:

- Electrical storage is, per kWh, more expensive, but is more flexible in its output. The electricity can be used to produce heat (via a wide variety of heat sources) and can also be used for most other electrical supply purposes, it has low degradation/standing losses but is restricted to receiving energy only from electrical sources.
- Thermal storage is generally cheaper, per kWh stored, is restricted to energy release as heat and suffers from degradation over time, that is, a hot thermal store cools down and loses heat, even when it is not being used. It can receive energy from both electrical and heat sources.

Controlled charge/discharge

Controlled storage is the main category of system in energy systems design, that is, the degree to which a storage system is 'charged', and then the rate and depth of the discharge are all manageable.

Uncontrolled charge/discharge

As well as controlled heat storage (i.e. managed charge and discharge from the store, used normally for DHW and/or space heating), there is also a form of thermal storage in every building – the thermal mass of the building.

Controlled charge/discharge

Electrical storage

Batteries are the main electrical energy storage system used in buildings. Historically, commercial buildings have used UPS batteries to provide back-up power for IT systems in the event of a power outage. These have been expensive, mostly based on lead acid batteries, and only of use in the event of an outage.

The development of large-capacity lithium ion batteries for electric vehicles (EV) has opened the way to building battery storage using the same mass production systems. These can be split into two types – dedicated building battery units and EV-based, dual-use batteries.

Building battery

A building battery system is normally comprised of three elements:

- An inverter – bidirectional. To charge the battery, it converts AC (or DC) into DC at the battery voltage. To discharge the battery, it converts the battery DC to the building AC voltage, syncing the voltage and frequency to the mains supply.
- A BMS (Battery Management System). This monitors the health of the batteries and their state of charge and controls the rate of charge/discharge to maximise the battery life. One BMS may be connected to multiple batteries and share the load across the batteries as required.
- The battery or batteries. At least one battery is required but for typical building systems more than one battery is often used. Each battery may be 2.5–6 kWh capacity, so a 20 kWh capacity system could need four to eight batteries.

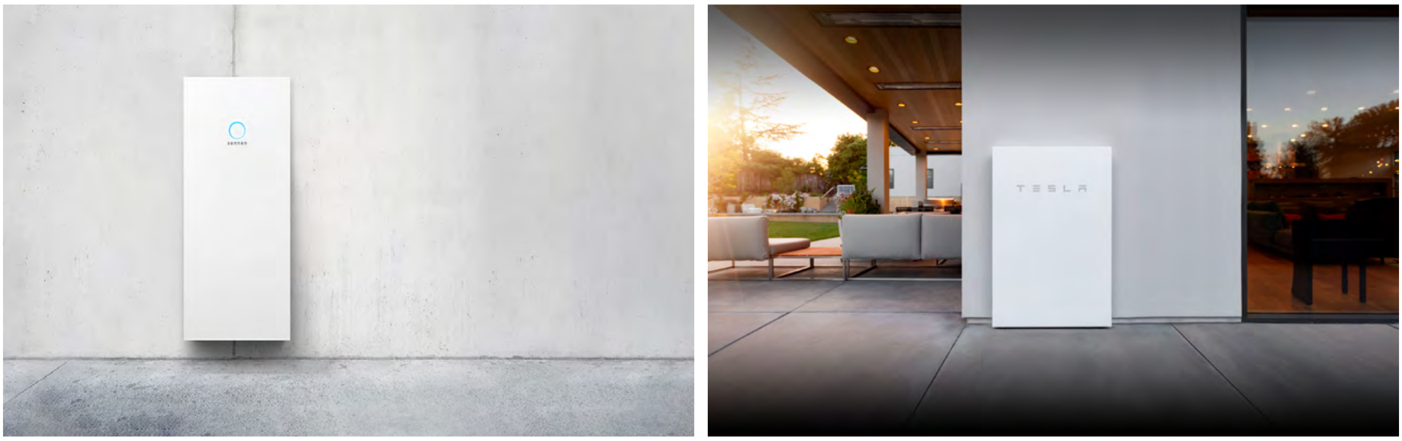
Key features of a building battery system include:

- Potential for the inverter to be shared with other systems. A ‘hybrid’ inverter may be both a PV inverter and a battery inverter – it is connected directly to both sub-systems. A standard PV inverter acts much like a battery inverter in discharge mode, so it is usually more economic to have one hybrid inverter rather than two dedicated PV/battery inverters.
- Potential for direct DC/DC conversion for battery charging. A PV system produces DC electricity. There can be efficiency savings if DC/DC conversion is used for charging, rather than DC/AC and then AC/DC. The inverter still needs to carry out AC/DC for battery charging from the mains, and DC/AC for discharge.

- Potential to use longer-lifetime lithium battery chemistries that avoid the use of conflict minerals. There are two main families of lithium battery chemistry used in building systems (out of the six available types):

Lithium Nickel Cobalt Aluminium Oxide (NCA). NCA batteries are high energy and can deliver high current for extended periods. They have been the main chemistry used for EVs. When an EV is accelerating, it may be discharging at the rate of 90–120 kW (i.e. 10–15 times more instantaneous power output than a building battery system will require). An issue with NCA is the use of Cobalt – a strategic mineral that is often mined in conflict zones.

Lithium Iron Phosphate (LFP). LFP batteries are less suited to very high-power output but are inherently safer (they have a lower thermal runaway temperature) and often have a longer lifespan, especially as the depth of discharge has minimal impact on lifetime.



sonnenBatterie use LFP whilst the Tesla Powerwall 2 uses NCA batteries

Image credits: sonnenbatterie.co.uk; tesla.com

For both types of battery, managing the charge/discharge conditions is important to maximising lifespan. When used in an EV, this can be especially challenging – an EV BMS has to control the battery temperature and the rate of discharge, together with the demand for ultra-fast charging to minimise EV fuelling stop delays. In a building, it is easier to run with 'ideal' conditions – the battery is housed within the building, at a temperature that is stable, and the charge/discharge rates are relatively low, so the battery and its associated electronics is not as stressed as for EV duty.

The trend is for LFP batteries to be used in building systems, rather than NCA, but both chemistries are in widely marketed mainstream products.

Vehicle battery

An EV battery system comprises the same three elements as a building system, but these are all integrated into the complete vehicle. The primary purpose of an EV is to power the vehicle (i.e. of no apparent relevance to buildings). However, there is a move to make EV battery systems multifunctional (i.e. V2X (Vehicle to Anything). At the heart of this is V2H/V2B (Vehicle to Home/Building).

If a building has an EV charger, this is similar to the inverter in a building battery system, converting AC mains to DC for the EV battery. If the inverter is made to be bidirectional – very similar to the building battery inverter – then the EV battery can be managed to discharge back to the building mains voltage AC system. This does not provide any benefit to the EV, so enabling this functionality has not been a priority for EV manufacturers, but for a building it has great potential.

If an EV is plugged in adjacent to a building for much of the day and night, then it can act as a building battery system. The key differences are:

- The EV may drive away at any time, so the building systems need to be able to manage without the battery.
- The EV will usually need to be charged to a defined level prior to driving use, that is, the planned use of the EV needs to be managed alongside the building needs. If the EV is due to be driven soon, then it may not be possible to discharge from the battery for V2H use.
- The EV battery capacity is large, in comparison to most building battery systems. A typical EV battery is in the range of 50–80 kWh capacity, 7–10 times the typical domestic battery system. This means that:
    - the daily domestic building drawdown may only be 20–30% of its capacity
    - the EV battery is able to absorb most/all of a PV system output, even on a sunny summer day
    - in comparison, a much smaller typical domestic battery system may only be able to take up a share of the daily electricity load, and will not store a summer day's PV output.
- An investment in an EV battery (i.e. purchase of the EV itself) gives a home battery 'for free'. If the EV is a used vehicle, then the upfront cost saving is even greater.

A development from V2H/V2B is V2G (Vehicle to Grid). This is actually an overlap with B2G (Building to Grid), as strictly, the vehicle is supplying electricity to the building, and then the building may choose to supply electricity back to the grid. When a PV system exports to the grid, this is B2G. The export could therefore come from a building battery or an EV battery rather than a PV system – for the grid, it is just an export from the building.

The reason V2G has become of interest is twofold:

- The total aggregated capacity of hundreds of thousands of V2H EVs, plugged in, is significant, in grid terms. This means that a fleet of 'V2G' EVs can be used to store excess electricity when production is too high (e.g. nuclear base load, plus high winds creating large output from wind turbines at night), and then can be used for peak shaving output to the grid, instead of powering up standby gas-based generators. One EV will not make a difference but thousands of EVs, managed transparently by a service, could be significant.
- For the EV owner/operator, allowing the EV battery to be used as a grid battery, when needed, is a potential income stream – the battery is charged when wholesale electricity is cheap, and discharged when it is expensive. The managing service will take some of the difference but the EV owner will also derive an income, subsidising the cost of the EV.

Octopus EV's Powerloop project trialled Vehicle-to-Grid technology

Image credit: https://octopusev.com/powerloop

The challenges for both V2H and V2G are:

- Battery life. For most homes, V2H usage, with a 50–80kWh capacity battery, is not going to be significant in reducing the battery lifespan, which is why EV manufacturers are now V2H enabling their core EV platforms. However, V2G may be different: an EV that is used for a 60% cycle (charge/discharge), twice per day, would be carrying out the equivalent of 440 full cycles per annum. This, repeated over many years, is of the same order as the expected lifetime of a battery (i.e. the battery could be 'worn out' by the V2G usage, without the EV ever having been driven).
- Management. Both V2H and V2G require the EV charging to be managed to a higher level than is provided by standard EV charging.

The management system will need to work with:

- a plan for the maximum charge/discharge usage of the EV battery to ensure that battery life is maintained
- control over charge/discharge rates
- timing of charging (e.g. should the EV be charged overnight on a low-tariff rate or should this be delayed to allow for PV charging the next day as the forecast is for good weather/ high solar gain tomorrow?)
- a plan for EV driving usage – both pre-planned/learnt and also ad hoc
- a plan for battery discharge usage (e.g. the system may need to learn the typical battery use for the building, by time of day/day of the week/season to assist in automatic decision making for charge/discharge/timing).

The requirements for a V2G management system are different, in emphasis, to V2H management – the grid is acting like two additional systems on the building, equivalent to a huge PV system that can charge at any time, and a huge electricity load (like a bank of immersion heaters) that can also be discharging at any time. The trigger for when these could be used is coming from the grid, not the building – the grid request for charge/discharge needs to be moderated by the building V2G management system.

A feature of battery usage, both building and EV types, is that it can increase the efficiency of three-phase installations. There is a grid limit of 3.6 kW for PV systems when run on single phase, so larger systems need to be three phase, which will become the norm for many buildings as PV panels become more efficient, and planning regulations require self-generation. However, most of the building loads are single phase – all on one phase or split across the phases. This reduces self-consumption, unless a three-phase battery system is installed.

For example, a 3 kW kettle is switched on and the PV is generating 4 kW. This is split across the phases – 1.33 kW per phase, so the kettle draws 1.33 kW from one phase and 1.67 kW from the grid, even though the PV generation exceeds the consumption. If a three-phase battery is installed, the inverter discharges from the battery bank to suit the demand – if there is only demand on one phase it only discharges to that phase. So with a three-phase battery installed, the 3 kW kettle draws from the battery and the 4kW PV output charges the battery – the battery acts as a phase balancer. Most domestic equipment is single phase – even a three-phase induction hob splits the phases across the hot plates, so it is likely that the only household equipment installed as three phase will be a heat pump.

Thermal storage

Thermal storage systems vary widely in type and format. They can be categorised by the storage medium – water (i.e. a liquid), phase-change material (solid/liquid) and solid. They can also vary in how the energy is added to the storage medium and how it is then extracted, and at what temperature.

Thermal storage is the most common energy storage in the UK, much more common, and significant, than electrical energy storage.

Water based

A water-based thermal storage system is either:

- Based on a vessel that contains potable water (i.e. the water in the store will be dispensed, to be consumed/used directly (as DHW)).
- Based on a vessel containing 'static' treated water – the water is acting as a thermal battery to accept energy/give up energy and is sealed into the system. A system based on a sealed water volume is termed a 'thermal store'.

The reason for water being the liquid of choice, even in 'thermal stores', is multi-fold:

- Water has a very high specific heat capacity – it is easy to heat, it has a low viscosity so can easily be pumped, it is a very practical and versatile heat-transfer medium. The same fluid – water – can be used as the storage medium and also the heat transfer medium (e.g. for space heating emitters).
- A system can be installed, empty, and filled on site from the building mains water supply. There is a great logistical advantage in being able to work with lightweight components, and then fill on completion, with a storage medium that is essentially zero cost.
- Flexibility in temperature application. A water-based store can be operated over a range of temperatures (30–90 °C), and if required, can be used to provide different temperature outputs from the one volume, based on stratification of hot water – the hotter water naturally being in the upper portion of a tank.

Vented hot water cylinder

Historically, the standard 'hot water tank' was a vented cylinder, often copper, gravity fed with cold mains water from a header tank. The tank water was heated by an internal tank coil (copper). The water flowing through the coil was in turn heated by a gas/oil boiler or solid fuel stove/back boiler. The tank also had a 3kW electric immersion heater – either as a primary heat source or a backup to the boiler.

The problems with this system were:

- Being vented, with a gravity feed, required a cold header tank located above the hot water cylinder.
- The pressure of the hot water dispensed from the cylinder is based on gravity and on the height of the header tank above the tap/appliance using the water. In a typical home, a shower on the first floor would only have 1 metre of head, so the hot water flow was inadequate. A shower in an attic room would not be possible, as it would be above the header tank. If more than one person were using the hot supply (e.g. running the kitchen tap), the shower flow would be reduced, so temperature control of a shower was problematic. This led to a widespread adoption of auxiliary shower pumps, to create a 'power shower'.

The vented gravity-feed hot water cylinder was widely used in the UK, but in the rest of Europe unvented cylinders were more common. Regulations in the UK were improved and in new builds and renovations, the unvented system took over.

Unvented hot water cylinder

An unvented cylinder is directly mains water fed. The cylinder is a pressure vessel, often stainless steel. Normally the mains water supply pressure to the building is set to three bar, and the hot water cylinder has pressure and temperature relief valves to ensure that if either the pressure or temperature are excessive, water is vented to drain.

Because water expands, when it is heated, an unvented cylinder must be connected to an expansion vessel (internal or external) to keep the pressure approximately constant, as the water is warmed. Without this, the pressure would rise and vent off hot water.

Like the vented cylinder, the unvented cylinder is heated by one or more internal coils, plus one or more immersion heaters. Cylinders can be quite complex – to allow for multiple heat sources – for example, both a boiler coil and a solar thermal coil.

The key advantage, and difference, for the unvented cylinder is that the hot water is supplied at the same pressure as the cold supply, so the flow rates are good (and the same), and mixing devices (shower, bath filler, basin mixer tap) give a consistent balanced output.

The disadvantage of the unvented system is that, being pressurised, the tank has to be built to a higher standard, is often stainless steel, requires an expansion vessel and should be checked regularly, due to being a pressure vessel.

Thermal store

The third version of the hot water tank – the thermal store – is fundamentally different. It may look very similar to the unvented cylinder but the water in the tank is static – it is a thermal battery. In a standard hot water cylinder, the stored volume is the potable water, and the hot water heating coil is treated/static water. In a thermal store the situation is reversed – the stored volume is static water, and a coil contains the potable water being heated as it passes through the tank coil.

However, there are many variations on this design. These cover:

- **Method of heating the store water**
    - Directly – the water can be pumped to/from a heater (such as a gas boiler or heat pump).
    - Indirectly (coil) – the tank contains one or more heating coils, just like a vented hot water cylinder. The water in the boiler circuit is separate from the water in the store.
    - Indirectly (heat exchanger) – the tank water is pumped to/from an external flat plate heat exchanger, the other side of which is a separate heating circuit. For example, a solar thermal system will typically be run using 50% water/glycol. The heat exchanger allows for efficient heat transfer between the two circuits, each has its own speed-controlled pump.
- **Method of heating domestic hot water (DHW)**
    - Indirectly (coil) – the tank contains a large surface area coil. Mains cold water is passed into the base of the coil (about halfway up the tank) and leaves near the top of the tank, so is heated by the store water as it flows through the coil.
    - Indirectly (heat exchanger) – the mains cold water passes through a ‘FriWa’ unit – a heat exchanger (HeX), with sensors (flow and temp), and a pump on the tank water side of the heat exchanger. The pump is controlled so as to pump hot water from the top of the store through the HeX, heating the cold mains water, and so cooling as it does so. The colder return is sent back to the base of the store. The flow rate is controlled, to give a programmed hot water output temperature. Typically, the flow from the tank is 55 °C, the return to the tank is 25 °C.

- **Method of heating other demands**
  - A thermal store may be only used for DHW production (like the previous vented/unvented hot water tanks) but it can also be used as a thermal buffer/battery for a space heating system, either stand alone or in combination with DHW production.

Most heating systems, such as gas boilers and heat pumps, have a ‘sweet spot’ for operating efficiency – if they are not operated under this condition, their performance suffers. If a heat source is directly coupled to a heat demand, and they are not perfectly matched (e.g. some radiators have shut down when the room is up to temperature, so demand drops), then the heat source has to reduce its output, either by operating in a frequent start/stop mode (‘short cycling’) or, if this is possible, by running at reduced capacity.

For example:

- **Condensing gas boiler**
  - To condense efficiently, the return should be at least 11 °C cooler than the flow. If a boiler is connected directly to a radiator circuit that has only a 5 °C drop, then the boiler operation is sub-optimal.
  - The boiler will have the ability to run over a range of burner power, so it can operate at 1/3rd power when needed, but this is usually less efficient than running closer to full power. Every time the boiler starts and stops it wastes fuel, so short cycling is inefficient and will reduce the boiler lifespan.
- **Heat pump**
  - Every heat pump (HP) has a highest efficiency point, for the ‘delta’ temperature difference between the output flow and return. Depending upon the heat pump design and working fluid, this will vary. It also depends upon the demand temperature/source temperature, so if the heat pump is operated with a ‘delta’ that is non-optimal, the heat pump efficiency (Coefficient of Performance – CoP) is reduced.
  - Many heat pumps are variable speed – inverter controlled. They can operate over a capacity range (e.g. 2–6 kW) based on the compressor being run over a speed range (e.g. 30% to 100%). Although the HP can operate at different speeds, the CoP varies as the speed changes and the relationship is often not obvious.

  The optimal speed may be at less than 100% and may vary according to the operating temps (source and demand). A HP 'auto' setting may be convenient but sub-optimal, operating the HP at either 100% (start-up) or 30% (tick-over), when the optimal CoP speed may be 50–60%.

  - A heat pump only operates efficiently once it has circulated the working fluid. Every time it is stopped/restarted, it consumes energy for little gain, so short cycling reduces efficiency and also shortens the compressor life, as the lubricant supply is only stable once the compressor is at speed.

When energy costs were low, adding 'complexity' to a system to enable it to operate at optimal efficiency and to maximise the equipment lifetime was not thought economic. As costs have risen the situation has reversed. Now it is important to ensure that the heat source is run as effectively as possible – highest CoP and longest lifetime.

An extra driver, now, is variable energy pricing. Gas is supplied at the same price, day and night, and has to come from the grid so a gas boiler can be run on-demand. A heat pump uses electricity and this could vary greatly in cost. Depending on the time of day, a variable tariff could produce a factor of three difference in price, and if the supply is self-generated (PV) it could be 'free'. However, this means that the times when it is cheapest to run the heat pump will not necessarily be the times when space heating demand is required.

Maximising heat source efficiency and minimising electricity costs is done by disconnecting and time shifting the source from the demand using a buffer (a heat battery). An electrical battery allows for time shifting of the electricity supply, but only a heat battery can separate supply and demand (maximising the CoP). The result is that a space heating buffer may be a stand-alone store or may be merged with a DHW store, depending upon the system design.

Phase-change material based

Phase-change stores, unlike liquid and solid material storage, are based on the exploitation of latent heat. A solid or liquid will absorb energy, and its temperature will rise, based on 'sensible heat' (i.e. Specific Heat Capacity of the material). Every solid has a melting point. When its temperature rises to this point, additional energy is used to melt the material, not to raise its temperature further. Once the material has melted (e.g. ice becomes water), a further injection of energy will raise the temperature of the liquid.

A key feature of latent heat – the energy used to melt the solid – is that it is disproportionately large in comparison to the sensible heat used to raise the temperature. A phase-change (PCM)-based store is therefore based on the concept of melting a solid, to absorb and store heat, and then re-solidifying the liquid to discharge the energy. Typically, 80–90% of the stored energy in such a store is released via the phase-change process rather than from cooling/heating the solid or liquid.

The challenges for a practical PCM store, used for DHW production, are:

- Selection of a material that melts at a usable temperature, to serve the purpose of the store. The material also needs to be non-flammable.
- The material needs to be chosen to maximise the latent heat, per unit volume.
- The internal structure of the store needs to contain water pipework and electrical elements (i.e. the equivalent of a hot water tank immersion heater). The pipework needs to have a good coverage of the stored volume. Unlike a water-based store, the solid material, as it is heated, cannot move by convection, so heat has to be transmitted to more distant material via conduction (i.e. positioning the pipework is critical).

The resulting design of a PCM store is normally:

- A relatively compact, rectangular/cubic box.
- High-grade insulation – often vacuum insulated panels that are easiest to use with flat-sided stores.
- A selected latent heat temperature of approximately 58 °C for a DHW store. This means that the material absorbs/releases the latent heat between about 55 °C and 65 °C – the store is heated to 65 °C, to store heat, and cooled to 55 °C to release the heat.

The key differences between a PCM store and the more conventional water-based store are:

- The PCM store is analogous to a water-based internal coil thermal store rather than a hot water tank.

- The PCM store is heavy to ship and install and has to be manufactured with the PCM material onboard, unlike a water-based store that is filled in-situ. A PCM store can weigh 120–240 kg and needs specialist moving equipment to install the unit and to remove it when it requires replacement.
- A PCM store contains electronic controls – it is not a 'dumb' tank, unlike most water-based stores. The electronics, and their associated firmware/software, are likely to be the first point of failure. If a tank is intended for a 50-year life, then there needs to be a roadmap/plan for the controls/software to be replaced/repaired/updated during that time span, possibly multiple times.
- The PCM material has just one absorption/release temperature band (e.g. 55–65 °C. Water is inherently flexible – a hot water store can release heat/absorb energy at any temperature over the range 30–90 °C. This has implications for:
    - o matching the PCM to heat sources
    - o matching the PCM store to DHW delivery
    - o use of the store for multiple demands.

PCM stores will always be more expensive than water-based thermal stores – they are inherently more complex and the materials used are more costly – but the key differences that are marketed as advantageous are:

- Space – a PCM store is more compact per kWh stored energy, though this difference is not as significant as is often claimed.
- Heat loss – the PCM store, using vacuum insulated panels, has a lower standing heat loss.
- The PCM store is not a pressure vessel – it does not require an expansion vessel, nor does it need periodic vessel inspection (though, being more complex, it may require more long-term maintenance).

As well as dedicated PCM stores, there are also hybrid PCM/water thermal stores. These are based on a standard water thermal store, into which PCM 'modules' are 'posted'. The modules are hermetically sealed plastic (PP or HDPE) containers (often either balls or rods) of PCM material. Balls may be 50–60 mm diameter, rods may be 30 mm diameter/240 mm long. The modules are 'posted' into the store via the immersion heater opening or a dedicated small hatch. The modules may be denser, or less dense, than water. If light, they will float and stay at the top of the store. If heavier, they sink and have to be retained in place by a mesh built into the tank.

The concept of the hybrid PCM/water store is that it is potentially cheaper and simpler than a pure PCM store and is more flexible as it retains many of the advantages of a water-based store. Also:

- The PCM modules can be introduced on site, so the store is still lightweight to install.
- There is no need for specialist internal pipework systems, and nor are there any electronic controls/software/firmware. The water surrounding the modules is the heat-transfer medium. This gives the store a much longer strategic life and is not reliant on the PCM store manufacturer still being in existence, in 30–50 years' time.
- The amount of PCM material used can be tuned to the application. A store that is 100% packed with modules is typically 50% PCM by volume (rods) or 60% (balls). However, just the top 50% of the of the store may be PCM (e.g. floating balls) which allows the bottom half of the tank to be used for space heating water, and FriWa DHW production return water (25 °C). PCM would be wasted in the lower zone.
- The hybrid store can be used for both DHW and space heating.
- Existing water-based thermal stores can be retrofitted with PCM modules, provided they will fit through the immersion heater opening.

A 50% packed hybrid store typically has the thermal storage capacity of approximately 2.4 times that of the standard 100% water-based store.

Solid material based

Space heating

Homes have used solid-based heat storage for many years – at one time, electric night storage heaters were widely used. These are well-insulated heavy units that contain a heat-absorbing medium, such as mineral/ceramic blocks, plus electric elements (to heat the mineral), and an air circulation system to release the heat via convection. Typically, the unit is heated overnight using low-tariff (Economy 7) electricity then flaps are opened/shut to allow the heat to be released, when required, during the rest of the day, ready to be reheated the following night. These units are only for space heating, not DHW production.

The storage heater has evolved, the materials have improved, together with heat-extraction systems and controls. They are still generally thicker (and much heavier) than a standard water-based radiator but are much more compact than the units of the past.

The internal storage 'bricks' (usually ceramic) are heated to a relatively high temperature so the storage capacity of a single radiator can be high (15–20 kWh). These units are a combination of a heat store and a space heating emitter, that is, they are not a stand-alone store.

Domestic hot water (DHW)/Space heating

An alternative iteration of the same concept is the solid-state electric boiler. A unit, typically floor mounted, contains high-temperature storage blocks, electric elements and a heat extraction system. The difference between this and the storage heater is that the heat is extracted via water pipes, either as DHW or as space heating water. It is then analogous to an electrically heated water-based thermal store and an electrically heated PCM store.

The key difference is that the storage medium is raised to a relatively high temperature. The energy density is higher, per unit volume, than can be achieved with either water or PCM units. The standing losses are higher, even though the units are well insulated due to the high internal temperature.

As with PCM stores, a solid-state store does require electronic controls and hardware such as fans/pumps/valves and, similarly to the PCM unit, it is heavy, typically 300–400 kg for a domestic unit.

Mass storage

An alternative to a domestic scale solid-state store is to use large-volume storage, either relatively simple buried volumes or more sophisticated industrial-scale plants.

The simplest form of buried volume is to use the ground (i.e. soil, sub-soil, clay and rock). For example, an established method of using ground-source heat pumps underneath high-rise buildings, such as city centre office blocks, is to use the deep concrete piles below the block as a heat source and a heat dump. In winter, pipework within the piles collects heat from the ground to be used by the heat pump for space heating. In summer, the heat pumps operate in reverse to cool the building, and hot water is sent to the piles. The surrounding sub-soil and rock are heated by the piles – some of the heat is then lost as it gradually dissipates outwards over the autumn, but when the heating season returns, the piles are able to collect some of the heat that was dumped in the summer. Without a heat-dump cycle, it is often found that the ground cools year on year as the natural rate of replenishment is less than the extraction rate. However, with the summer dump cycle, the ground temperature remains constant across the years and also provides a low-cost method to remove summer excess heat from the building, assuming the pile pipework system is already in place for the winter heating.

Another way to carry out the same system, on a smaller/domestic scale, is to place a dedicated water pipework system in the ground below or alongside a house. Unlike the office systems, this is purely used for by the heat pump, it has no structural purpose and is relatively shallow (1–2 metres deep). In a domestic situation, the ground heat replenishment may come from a solar thermal. These have a tendency to over-produce heat in summer if they have been sized for the spring and autumn, so the excess heat can be stored underground. Only some of the heat will remain for the winter heat pump use and the challenge is to ensure enough is stored that the system is worth the investment.

On an industrial scale, high-temperature mass storage can be used. The highest temperature systems are based on carbon blocks within a protective atmosphere – heated to 2000 °C. Lower-temperature systems run in the range 150–500 °C. These may be used for process heat purposes or for heat network thermal storage and are typically purpose designed for the application.

Uncontrolled charge/discharge

Thermal mass

As well as controlled heat storage (i.e. managed charge and discharge from the store, used normally for DHW and/or space heating), there is also a form of thermal storage in every building – the thermal mass of the building.

Every building receives heat from the outside – from solar radiation – and also usually generates heat internally, from occupants and equipment. The greater the south-facing window area, the higher the insolation gains. The thermal mass of the building is a measure of how well the building can absorb heat gains, and then discharge these back to the internal environment. For example, a low thermal mass home (e.g. timber frame) with extensive south-facing glazing could have high-temperature rises in the main rooms on a sunny day and then, when the outside temperature drops to zero overnight, the room temperatures tumble. In contrast, a high thermal mass building (e.g. mass concrete), under the same conditions, will heat up less in the daytime and cool less overnight. More of the heat gain during the day is absorbed into the building fabric to be reradiated/conducted/convected overnight. It is generally considered that there is no inherent downside to a building having high thermal mass.

Ideally, a building should have a high thermal mass without incurring additional/high fabric build costs, and without adding excessive embodied carbon. The thermal mass should in turn reduce the operational carbon use, as the building is naturally better temperature controlled.

There are two main types of thermal mass – those based on solid materials (usually the building fabric that is already in place as part of the basic design) and those based on additional phase-change materials, added to the design specifically to increase thermal mass.

Solid material based

The ideal material to create thermal mass in a building is an internal wall or floor that is close to the internal surface, is not covered with insulation, has high density and a reasonable thickness. In traditional domestic house construction, this would cover:

- concrete block inner skin walls, covered with plasterboard
- concrete ground floor, screeded, then tiled/boarded
- concrete beam and block-separating floors.

These elements of the building fabric are placed for their structural use, not because of their thermal characteristics, but the thermal mass they give is a welcome bonus. A dense concrete block weighs 2000 kg/m^3, a 3.5m x 3.5m room with two external walls (one window) and a concrete floor/ceiling, will have a concrete mass of approximately 9 tonnes. This will store 2.2 kWh per °C temp rise, so a 5°C rise stores over 10 kWh to then be released as day turns to night. In a home with five main rooms, this would be 50 kWh stored and released. In reality, it takes time for the heat to penetrate the concrete, and to leave it, so there are two effects – short term (reduction in day to night swing) and longer term (creating a comfortable average room temperature).

The problem comes when this house design is changed to a low embodied carbon alternative – timber frame, with timber walls and floors. The thermal mass is minimal in comparison to the concrete-based home and the result may be an increase in operational carbon/energy costs, due to increased duty for heating and cooling systems. The challenge is therefore – how can higher thermal mass products be incorporated into building fabric without a significant increase in embodied carbon?

An example of a solid-based lower embodied carbon material is hempcrete, which can be used as an insulator in ultra thick timber frame walls (350 mm) and has a U value performance equivalent to about 100 mm of polyurethane foam board. Unlike the board, it has mass. It is not as good a heat sink as concrete, but much better than lightweight insulation products.

Hempcrete blocks

Image credit: https://www.isohemp.com/en/hemp-blocks-naturally-efficient-masonry

Another alternative is to use reduced/low carbon concrete products – the cement industry is starting to formulate low carbon cement/concrete, which combined with the use of recycled aggregates, means that concrete based walls and floors can be much lower embodied carbon, compared to previously, whilst retaining their good thermal mass properties.

The whole topic of low embodied carbon/high thermal mass materials is going to be of growing interest and is still in its infancy.

Phase-change material based

Just as phase-change materials can be used in dedicated thermal stores/hybrid stores, instead of water-based stores, so the PCM can be built into the building fabric as an in-place thermal store. The PCM material is normally a wax-based substance that is incorporated into building boards, such as plasterboard, so that it is in close contact with the room air and incoming solar radiation – for example as a ceiling. The wax is held in the board as microbeads and melts at about 23 °C to absorb heat, and then as the room cools below 23 °C, it solidifies and gives back the absorbed energy.

If a standard plasterboard is heated by 5 °C (19 to 24 °C) it absorbs 12 Wh per m2. The same thickness of concrete would absorb 37 Wh, so three times better, but a wall board containing PCM beads absorbs approximately 105 Wh – a factor of three better than the concrete, nine times more than the plasterboard.

PCM wall boards are not cheap as they are not priced to be affordable alternative to plasterboard. They have to be considered as a building services item that, if used well, can reduce the need for some heating and cooling, especially in inherently low thermal-mass buildings such as timber frame with external insulation.

PCM material can also be used in a more active system. Instead of being built into the fabric, it is contained in cassettes (e.g. plastic moulded sheets, in a matrix), through which air can be blown. These can be housed in a ceiling void. There is an electricity consumption to run the system, but the material can be used more efficiently.

The main limitation on PCM use for thermal mass is cost. There are no building regulation drivers that force it to be used, the units/products are relatively expensive, and they fall between the professions. An architect does not design in a PCM ceiling board as this is part of the space heating, but an M&E consultant does not specify it as it is part of the fabric.

Conclusion

Homes built in the last two decades have typically had little or no energy storage:

- no home battery system
- no EV charging/Vehicle to Home (V2H) system
- no hot water tank, as they use a gas combi boiler
- poor thermal mass, due to the use of lightweight construction systems.

In 10 years' time a home is likely to have:

- a home battery system, linked to a solar PV system
- EV charging, configured to operate as V2H storage
- a thermal store, probably water based, with the option of added PCM balls/rods, and a 'FriWa' DHW production unit
- a heat pump, rather than a gas boiler, with either an associated buffer tank or using a section of the thermal store.

All of these are currently available (V2H is about to go live within the next year) and will have a significant effect on the way homes are run, and the energy cost reductions that are needed.

The issue of thermal mass – how to provide it in a lower carbon way – is less certain but likely to be a topic of interest to the industry over the next decade.

About Build Net Zero Now

The Build Net Zero Now campaign, led by the Good Homes Alliance, aims to empower progressive local authorities, housing associations and housebuilders, and their supply chains, by providing them with the knowledge and tools to deliver net zero housing.

Following a year-long series of topical events and targeted outputs, including new and freely available net zero case studies and design briefs, phase one of the campaign concluded at the GHA Build Net Zero Now Conference in October 2021.

For phase two, three working groups were launched on net zero finance, energy solutions and planning & placemaking and tasked with delivering a targeted and much-needed output that will help accelerate the delivery of net zero housing.

Outputs include guidance on energy solutions, a 'mini manifesto' and report on how the finance sector should adapt to accelerate the delivery of net zero homes, and a new web portal showcasing the progressive work of local authorities in setting net zero and Passivhaus planning policies.

The campaign outputs have proved vital for the 30+ members of our fast-growing Vanguard (Local Authority), Pathfinder (Housing Association) and Net Zero Developer (SME developer) networks from across the UK, who collectively represent 350,000 existing homes and 120,000 new build homes to be developed in the next 10 years.

Despite the success of the campaign to date, the need to accelerate the delivery of net zero housing is more urgent than ever.

To find out more about the campaign and phase 3 outputs, please visit https://goodhomes.org.uk/campaign/build-net-zero-now or contact Richard Broad: richard@goodhomes.org.uk.

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