Programme Area: Smart Systems and Heat

Project: WP1 Integrated Electrical Heat

Title: Integrated Electric Heat – Domestic Heat Storage: A Landscape Review

Abstract:

This report contains a landscape review of domestic heat storage, produced by NEF, is included as an annex to the final report of the Integrated Electric Heat project.

Context:

The Integrated Electric Heating Project provided a modelling tool to evaluate the opportunities and challenges for electric heating to meet UK household requirements. The tool will be used to create and evaluate upgrade pathways for a small number of housing archetypes informed by detailed information gathered from dwelling participating in the recent Home Energy Management System trial.

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Domestic Heat Storage: A Landscape Review

for the Energy Systems Catapult

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Executive Summary

The UK has embarked on an ambitious strategy to decarbonise the electricity grid so that we can heat our homes with electricity without high greenhouse gas emissions. This would mean we can be comfortable and meet the legally binding target for reducing greenhouse gas emissions by 80% by 2050.

Heat pumps and thermal storage will almost certainly be part of the transition to low-carbon heating in homes – because heat pumps offer high seasonal performance factors, and thermal storage can help to align periods of high renewable energy supply with periods of high demand for heat.

There are three categories of thermal storage technology:

1. Using ‘sensible heat’ (without any change of phase)
2. Using ‘latent heat’ (with phase change – e.g. from water to ice or wax to molten wax)
3. Using a thermochemical reaction (where a reversible reaction stores and then releases energy).

Latent heat technologies store more than twice as much energy per m^3 as sensible technologies, and thermochemical technologies store up to about seven times as much again per m^3. Thermochemical technologies also offer the advantage that insulation is less important. However, at present no thermochemical systems are available on the market. We expect such systems to be commercially available within the next ten years.

The average daily energy demand across all UK homes is around 11kWh a day for hot water, and around 70kWh a day for space heating. For retrofitted energy-efficient homes this falls to around 10kWh a day for hot water and around 15kWh a day for space heating. This suggests that a typical retrofitted home would need a storage tank from 0.05m^3 to 0.74m^3 (depending on the technology) to provide one day of heating. Allowing for tank insulation of 200mm, the external size of the storage would be around 0.37 m^3 to 1.55 m^3. These volumes can be scaled, so the internal tank volume for three days would be three times that for one day’s storage.

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We looked in detail at 13 technologies that could provide the necessary thermal storage (summarised in the Technology Matrix that links to this report). We considered both daily storage (energy stored and used within the a 24 hour period), and also seasonal storage (energy stored in summer to be used in winter). We also considered which technologies were appropriate for which heat sources and delivery mechanisms – like radiators, underfloor heating, or warm-air heating. We concluded that the most promising four technologies to pursue in the integrated electric heating project are:

1. Phase-change materials in a storage unit – using the Sunamp or other system to provide storage over a day or a few days.
2. A seasonal storage pit – using solar thermal energy to store energy from summer to winter.
3. Electric storage heaters – powered by excess solar PV and cheap Economy 7 electricity overnight.
4. A thermochemical system – included for its potential as a disruptive technology, which may need a buffer tank until system designs are refined.

1 Context

The Energy Systems Catapult (ESC) has recognised the need to design low carbon pathways, including low-carbon heating, to enable mass uptake of low-carbon technology in the home. Recognising the recent trends of retrofitting gas-fuelled combi boilers (half of all installed boilers) Palmer & Cooper (2014), the need for hot water tanks has become widely redundant. Many households have stripped out their domestic hot water (DHW) cylinders to repurpose the space (although sales of DHW tanks (c.400k per annum) remain stable, with around 11 million nationwide).

Solar thermal and electric heating are earmarked to meet the DHW and space heating requirements when the electricity supply grid is decarbonised. Heat pumps are largely touted as the leading electrical heat generation technologies due to their high coefficients of performance (COP). However, evidence (Welch, 2010) suggests that the relatively low-grade heat produced from a heat pump, operating efficiently, is insufficient to meet instantaneous domestic hot water demands, without supporting heating elements.

Therefore, when considering a whole house heating approach, the need for hot water storage has rearisen to act as a thermal buffer for the associated heat pump. Hot water cylinders can be re-used where they remain, however where the space has been repurposed or was never there, finding alternative heat storage systems is essential.

Further, although solar thermal can provide sufficient heat to deliver DHW and space heating on paper, peak solar thermal energy is misaligned with peak heat demand. Space heating is needed in winter evenings, when solar thermal energy is at its lowest. Daily (diurnal) and seasonal thermal energy storage solutions are required to broaden the provision of renewable heat for homes.

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As part of the wider low carbon pathways commissioned by the ESC, the following landscape study has been conducted to review the available technologies (commercial and conceptual) suitable for delivery of thermal heat storage for domestic buildings. The thermal storage technologies are aimed at satisfying the peak DHW and space heating demand – especially for the coldest periods when heat pumps alone would struggle to meet demand.

The portion of domestic heat to decarbonise is largely focused on the systems with fossil fuel boilers servicing DHW and/or wet heating systems. It is these systems where low-carbon alternatives are required. Existing all-electric properties are already on a low-carbon pathway, so long as the electric supply is decarbonised. The analysis of alternative heat storage media has therefore been largely focused on materials and systems that are suitable of delivering DHW or space heating via a wet system. It is envisaged these storage systems could be readily retrofitted into existing domestic systems.

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2 Scientific background

Three pathways for heat (thermal energy) storage have been established in literature:

- Sensible
- Latent
- Thermochemical

Sensible heat storage is energy storage without any phase change. Water is a common material, and increasing the temperature (heating) of water, insulating it so the hot energy is stored, and then extracting the thermal energy when heat is needed allows water to be used over and over again to store heat.

Latent heat storage is energy storage with phase change. For example, ice changing phase to water, which absorbs considerable energy, which can be released later when the water re-freezes. During phase transition, a material can absorb or release heat energy with minimal temperature change. Good insulation remains essential for efficient storage.

Thermochemical heat storage, as found in some gel heat packs, is achieved through management of stable, reversible endo- and exothermic chemical reactions. Heat is applied to separate two chemical compounds. These separate compounds can be stored stably at room temperature. Heat is released when the compounds are mixed and the reaction reversed, and insulation is not needed.

2.1 Thermodynamic limits

Due to the physical chemistry pathways at work there are physical limits to the energy storage capacity of different materials and systems. For each pathway the limit is based on:

- Sensible – material specific heat capacity, density and stable temperature difference available
- Latent – material enthalpy of transformation
- Thermochemical – chemical(s) specific enthalpy of reaction

Research continues to identify and optimise chemicals and compounds to enhance these physical properties. Evidence has been presented in literature (Kousksou et al., 2014) of the following energy storage densities:

- Sensible – 56 kWh/m^3 (*for water tanks*)
- Latent – 83-139 kWh/m^3
- Thermochemical – 111-833 kWh/m^3

2.2 State of development

The following table provides a helpful comparison of key performance characteristics of each heat storage mechanism.

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Table 1 - Comparing different types of thermal energy storage (adapted from (Kilkis and Kakac, 1989) and (Kousksou et al., 2014)).

	Sensible	Latent	Thermochemical
Storage density	Low, unless large temperature interval (56 kWh/m^3)	Moderate, increase at high temperature (83-139 kWh/m^3)	High (111-833 kWh/m^3)
Need for insulation	Yes	Yes	No
Operating temperature	Variable	Constant	Variable: low (30 – 70 °C), high (100 – 500 °C), higher if considering redox reaction
Technology	Available	Available for some temperature ranges	Prototype available
Lifetime	Long, indefinite	Often limited by cycling ability of the material	Depends on degradation, and possible side reactions, frequent problem
Transport-ability	Not normally	Short distances possible	Long distances possible
Heat losses	Depend on degree of insulation, long-term storage possible only with large scale storage	Depend on degree of insulation, long-term storage possible only with large scale storage	Losses through need for product cooling, long-term storage possible without additional losses

2.3 Heat storage materials

Numerous materials demonstrate viable heat storage capabilities and have been considered in this review, at least as a pilot prototype. Below these are briefly summarised with their strengths and weaknesses presented.

Table 2 - Comparing possible materials for different types of thermal energy storage.

Sensible: Liquid	Sensible: Solid	Latent: Solid/Liquid	Thermochemical
Water	Ceramic	Salt Hydrates	Adsorption materials: e.g. Zeolites
Glycol	Concrete	Paraffin wax	Absorption materials: e.g. NaOH solution
Molten salt	Brick	Fatty acids	Chemical (without sorption) materials: e.g. Vermiculite and $CaCl_2$ (composite salt in porous matrix)
Oil	Stone / Aggregate	Plant-derived wax/oil	$SrBr_2{\cdot}H_2O$ (hydration reaction of salt hydrates) (80kW/m^3 @ 50°C)
	Earth / Soil		$MgCl_2{\cdot}H_2O$ (hydration reaction of salt hydrates)

2.3.1 Sensible: Liquid storage

Sensible heat storage in liquids can provide both static thermal mass storage, and transfer heat from a store in one location to a point of use somewhere else.

Water is the most common heat storage material used in UK homes. It has a relatively high heat density, is inert and stable at human comfort temperatures, it can also serve as a heat transfer fluid, is abundant and very cheap. Due to water's broad strengths, any innovative alternative must provide a step change in any given area to achieve mass acceptance and uptake.

Glycol is used as an alternative heat transfer fluid in some systems, due to its higher boiling point; however its lower heat capacity, compared to water, limits its application. Glycol is therefore usually used as an additive to water to raise the freezing or boiling point.

Oil serves as a higher temperature storage and transfer fluid, suitable for systems with higher operating temperatures, however the low 'specific heat' (energy needed to raise temperature by 1°C), compared to water, makes water more suitable in <100°C applications.

Molten salt, as a material, provides high-temperature thermal storage and heat transfer fluid functionality. However, due to the high temperatures, the application is typically limited to grid level, concentrated solar systems and is not viable at the domestic level. Due to the inapplicability on a typical domestic level, it has not been analysed further in this Landscape Study.

2.3.2 Sensible: Solid storage

Solid sensible storage media benefit from stability at high temperatures or vast quantities to provide useful storage applications. They have lower specific heat capacities, and rely on a form of heat exchanger to heat transfer fluid to extract and input the heat.

Alumina ceramics have moderate heat capacity for a solid, but a very high melt temperature (c. 2,000°C) therefore they are suitable for very high temperature thermal storage systems.

Concrete, brick and other traditional building materials have comparable heat capacities with alumina, and comparably high melt temperatures. They are typically favoured for their strength and low cost when constructing a building. Due to being integral to the building construction, using the thermal mass is a side benefit, but one that can be leveraged effectively with appropriate building services systems.

Stone or aggregates benefit from their abundance, structural integrity and low cost. They are limited, however, by the need for integration with a heat transfer fluid and low thermal conductivity. Typical systems are coupled with heat pumps and buffer tanks to provide rapid response to heating demands.

Earth or soil benefits from being abundant and workable, as well as having moderate heat capacity and density. Higher levels of water in the earth/soil mix increase the thermal storage capacity. Significant excavation can incur high costs.

2.3.3 Latent: PCM

Phase change materials (PCM) are materials that change phase at a useful temperature for a given application, thus using their latent heat of transformation to increase the material's thermal storage

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capacity. Extensive research over the past 25 years has explored a variety of PCMs, characterised their physical properties and sought to enhance their strengths, whilst mitigating their drawbacks.

Salt hydrates are salt/water mixes that, with the right mix, can melt or freeze at desired operating temperatures. They are widely available, easy to manufacture and the lowest cost of available PCMs. They can suffer from separation overtime and are corrosive, limiting the form and material suitable for encapsulating the PCM.

Paraffin waxes, commonly C16/C18 blends, melt/freeze around room comfort temperature (20-24°C). They have higher thermal densities than salt hydrates but lower thermal conductivity. They are inert, but highly flammable, and therefore require a fireproof coating for integration into domestic applications.

Fatty acids have long been studied as PCMs, but with little commercial uptake.

Plant-derived oils, resins and waxes have received the greatest commercial attention of late. Derivatives of coconut, sustainable palm and other plant oils have demonstrated melt/freeze temperatures around room comfort temperatures. These oils benefit from being easily disposed of, non-corrosive and less flammable than alternative PCMs.

In the past five years a growing number of commercial products, leveraging the benefits of PCM, have become available. Some of the leading technologies have been included in the comparative analysis conducted in the second half of this assessment, see Section 3.3 below.

2.3.4 Thermochemical

Thermochemical heat storage provides the most significant enhanced performance compared to water, both with respect to theoretical energy storage density, but also the flexibility to store and transport the energy storage without insulation. Systems will still require insulation and heat transfer fluid at the extraction and delivery stages.

At the time of writing, no system was commercially available. Evidence of a pilot prototype system was identified during this review, therefore it is anticipated that in around the next ten years, commercial systems will be available.

There are three chemical mechanisms, each of which is stable and reversible thus can be used for thermal energy storage. These are adsorption (e.g. Zeolites), absorption (e.g. NaOH solution) and chemical (with sorption) reactions (e.g. hydration reaction of salt hydrates like $SrBr_2 \cdot 6H_2O$). Common reaction pathways researched up to now have used low cost and abundantly available reagents, with high energy densities.

Research continues to be focused on identifying optimum conditions and reagents for operating the reactions through modelling and lab-based research. Recommendations for design parameters are emerging, however there remains an extensive body of research required before commercially available technologies are ready.

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2.4 Meeting peak demand

To achieve 100% low carbon heat it is necessary to consider the suitability of the technologies with an awareness of the size of the demand. In a domestic context the demand for heat is characterised by DHW or space heating. Traditionally gas or oil boilers fuel DHW and space heating.

Demand for hot water is particularly sensitive to the occupancy pattern and number of occupants. On a high level, DHW demand varies based on the time of day, with morning and evening peaks. Weekday and seasonal variations also occur, although these are less dramatic than for space heating. 20% of DHW demand arises due to short, high-power demands, leading to heat loss in pipes. With significant variation, average showering takes 12 minutes (Buswell et al., 2013).

Space heating demand varies predominantly by season, with peak demand occurring on the coldest winter days. Daily profiles vary due to occupancy patterns, however little variation is observed by number of occupants. An unoccupied winter day space heating profile typically has a small morning, and larger evening peaks. Occupied winter days will see a smoother profile, increasing through the evening.

To characterise domestic heat demand two sources, Ofgem and Energiesprong, were consulted. Ofgem figures represent the current gas demand for UK properties, 23% for DHW and 77% for space heating. Based on an average house size (Savills, 2012) the figures in the table below were calculated. Energiesprong figures (extrapolated for four people) represent a retrofitted or highly-insulated new build home. For a sustainable low-carbon heating plan, a fabric-first approach should be adopted, so it is reasonable to assume that any low-carbon heating pathway should be sized to the 'Retrofitted stock' scenario.

Table 3 - Demand for space and water heating in existing retrofitted homes.

	Current stock	Retrofitted stock
Hot water *(daily)*	-, 10.6 kWh/day	190 l/day @ 50°C, 9.5 kWh/day[1]
Space heating *(annual)* *(daily)*[2]	137 kWh/m^2/year, 70.3 kWh/day	30 kWh/m^2/year, 15.4 kWh/day

The theoretical maximum storage capacity of each mechanism suggests sizing shown in Table 4 below. These sizes represent the theoretical minimum volume required to meet one full day's DHW and space heating demand for an average UK home (with four occupants).

Table 4 - Energy storage volumes needed for heating in existing retrofitted homes.

		Heat storage media only		Storage tank + 200 mm insulation	
	Capacity (kWh/m^3)	*Current stock*	*Retrofitted stock*	*Current stock*	*Retrofitted stock*
Sensible	56	2.17 m^3	0.74 m^3	4.14 m^3	1.55 m^3
Latent	139	1.09 m^3	0.30 m^3	2.06 m^3	0.87 m^3
Thermochemical	833	0.18 m^3	0.05 m^3	0.67 m^3	0.37 m^3

[1] Based on an average inlet temperature of 7.3°C, assuming no heat losses
[2] Based on 92.3m^2 (Savills, 2012), 180 day (6 month) heating season

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3 Heat storage technologies

3.1 Types of thermal store

Thermal stores are categorised by their function in the wider heating system. Typical thermal stores, their heat delivery, and heating method, are summarised below. Most are suitable for either individual homes or community based systems. Direct or indirect refer to the mechanism with which heat is transferred, for example, charging the thermal store either directly from the heat source (flame, electric element or sun) or indirectly (via a heat exchanger).

- (direct or indirect) *Integrated thermal store* – producing instantaneous hot water via a heat exchanger, for DHW and space heating, heating of the store is possible using more than one heat source
- (direct or indirect) *Hot water only thermal stores* – indirect water heating via heat exchanger, instantaneous hot water, multiple heating sources
- (direct or indirect) *Buffer stores* – applicable in community setting, to buffer flow of different heat sources and thermal demands

3.2 Scope

For the purpose of this landscape study, thermal storage technologies are defined as the combination of the thermal storage material (Section 2.3) and containment method, suitable for plumbing into a UK home. Promising materials not yet piloted in a system have not been included.

Due to the high power, short response time required for DHW there are two overarching methods; either a hot water buffer tank providing direct DHW, or via instantaneous water heating. Instantaneous water heating can be achieved through a burner, electrical heating element, heat pump or heat exchanger.

Space heating is characterised by a larger, less intensive demand profile. Space heating can be achieved through radiant, convective or conduction heating, so is more suited to a wider variety of heating systems. Space heating seldom uses a separate storage tank, except for electric storage heaters, instead most systems use thermal mass and insulation to retain heat as required.

Most heat storage technologies have been designed with specific accompanying heat generation, heat transportation and heat delivery technologies so as to meet a given demand. For example, domestic hot water tanks have been designed to store gas-heated water and deliver hot water directly. Adaptation is possible using heat pumps, buffer tanks, heat transfer fluids, heat exchangers and/or mixing valves.

Most of the heating systems requiring decarbonisation are systems with fossil fuel boilers providing domestic hot water and/or serving wet heating systems. Therefore, systems applicable to this context, i.e. with an equivalent function to a centralised hot water storage tank, have been prioritised. In addition, systems offering seasonal storage, boiler pre-heating, or direct storage heaters have been considered.

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Supplementary heat storage technologies, such as PCM wallboard or exposed concrete soffits, have not been included in the main analysis (Section 3.3.2) due to their differing function. Whilst these technologies are domestic low-carbon thermal energy storage technologies, they are most commonly used for cooling. Variation in system design could see these used to reduce heating demand, however a strict control strategy and regulated occupant behaviour would be required to ensure the added thermal mass would not inadvertently increase the heat demand. Even where carefully designed, these technologies would be unlikely to replace the need for a central heat store. A separate abridged analysis on thermal mass cooling technologies is included as Section 3.3.3).

3.3 Available technologies

To assess the suitability of available domestic heat storage technologies, the following comparative analysis method was followed. Full findings are contained in the associated Technology Matrix (.xlsx). A summary of technologies and their compatibility are included here.

3.3.1 Comparative analysis method

The comparative analysis was conducted following the method below:

1. Compile list of emerging and available thermal energy storage technologies
2. Categorise by application and filter out thermal mass cooling technologies or inapplicable technologies for domestic context
3. Research available literature, independent reviews and manufacturers' data to build an expert view
4. Analyse each technology against qualitative suitability and quantitative performance parameters (Appendix 7.1)

3.3.2 Heat Storage technologies

This section introduces the 13 heat storage technologies reviewed. It gives an overview of the description, the operational scale, main application and secondary applications. The operational scale ranges from room-by-room to community scale, based on known applications. It is possible to apply a number of these across multiple scales, in which case, the most common is referenced. Four broad application contexts are included: hot water cylinder equivalent, boiler pre-heater, seasonal storage and direct warm air delivery. Hot water tank technology was included as a baseline technology. Full comparative analysis can be found in the Technology Matrix.

In the sections that follow, the performance of each technology is considered in their respective application context.

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Table 5 – Technology summary table

Ref#	Technologies	Description	Scale	Application
HS01	Hot water tank – Baseline	Traditional hot water cylinder	Home	Hot water cylinder (or equivalent) - providing hot water for DHW and/or a wet heating system
HS02	Oil thermal storage tank	Specialist high temperature cylinder with heating fluid/water heat exchanger	Home	Hot water cylinder and system (or equivalent, e.g. high temperature) - taking high-temperature oil from solar collectors, providing hot water to a wet heating system and DHW through a heat exchanger, or as heating fluid through a pack bed thermal store
HS03	Phase Change Material (PCM) A58H in storage tanks	PCM balls added to a smaller hot water cylinder	Home	Hot water cylinder (or equivalent) - providing hot water for DHW and/or a wet heating system
HS04	Sunamp Heat Batteries	PCM with water heat exchanger, passing through units of differing melt temperature to deliver DHW	Home	Hot water cylinder (or equivalent) - providing hot water for DHW and/or a wet heating system
HS05	$SrBr_2{\cdot}H_2O$ Reactor	PhD prototype thermochemical storage system - with honeycomb heat exchanger and heat transfer fluid	Home	Hot water cylinder (or equivalent) - providing hot water for DHW and/or to a wet heating system / Seasonal storage
HS06	Magnetite heat storage	BRE/Dimplex lab-prototype all-electric hybrid heating & control system using thermochemical storage and heat pump	Home	Hot water cylinder (or equivalent) - providing hot water for DHW and/or to a wet heating system
HS07	Aquifers (water / sand) (heat storage)	Underground naturally formed aquifers, pumped and passed through a heat exchanger or heat pump, unsuitable for meeting peak heat demand, dependent on heat pump output	Community	Seasonal storage - charged during summer, discharged during winder, or suitable for serving community heating, or serve as pre-heaters to reduce heat pump load, also could provide DHW/wet heating via heat pump, heat exchangers and a buffer tank.
HS08	Borehole (earth / rock)	Underground excavated and covered aggregate stores, water pumped and passed through a heat exchanger or heat pump, unsuitable for meeting peak heat demand, dependent on heat pump output	Community, where aquifer unavailable	Seasonal storage - charged during summer, discharged during winder, suitable for serving community heating, as pre-heaters to reduce heat pump load, could provide DHW/wet heating via heat pump, heat exchangers and a buffer tank.
HS09	Pit storage (water or sand/aggregates)	Underground shallow excavated and covered aggregate stores, water pumped and passed through a heat exchanger or heat pump, unsuitable for meeting peak heat demand, dependent on heat pump output	Community	Seasonal storage - charged during summer, discharged during winder, suitable for serving community heating, serve as pre-heaters to reduce heat pump load. Also could provide DHW/wet heating via heat pump, heat exchangers and a buffer tank.
HS10	Pools as storage	Homes with pools can use the thermal mass of the pool water or ground surrounding the pool as thermal mass. High levels of temperature variation are unsuitable; however the large volume can offset some thermal storage demand.	Home	Seasonal storage - charged during summer, discharged during winder / Pre-heaters to reduce heat pump load. Also could provide DHW/wet heating via heat pump, heat exchangers and a buffer tank
HS11	Earth-Air Heat Exchangers (EAHE) - Thermal mass preheaters	EAHE's are air labyrinths sunken a couple of meters below the ground. Inlet air to a space heater is tempered as it passes through the labyrinth	Home	Pre-heaters to reduce heat pump load (Active thermal mass - tempering inlet air or water to reducing heating load)
HS12	Storage heaters Advanced – convection and time-of-use control	Ceramic cores, heated electrically, insulated, with louvres adjusted and fans blown over heated blocks when heat is demanded. Alternative to wet space heating.	Room by room	Electrically heated - space heating delivered via hot air
HS13	Storage heaters Simple – passive, timer on/off control	Ceramic cores, heated electrically, insulated, heat dissipated slowly throughout day. Alternative to wet space heating and intended to take advantage of cheap-rate electricity tariffs (like Economy 7) overnight.	Room by room	Electrically heated - space heating delivered via hot air

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3.3.2.1 Hot water tank equivalents (HST01, HS02, HS03, HS04, HS05, HS06)

Hot water tank equivalents refer to technologies that have a single storage facility containing dense thermal storage media. Each home requires a sufficient footprint, either internally or adjacent with access, to accommodate the storage facility, which varies by technology (11% ($SrBr_2 \cdot H_2O$ reactor) to 184% (oil thermal storage tanks) of the baseline hot water tank).

These systems can either deliver hot water directly (hot water tanks, PCM in storage tanks) or indirectly through a heat exchanger or mixing valve (oil thermal storage tank, Sunamp heat batteries, $SrBr_2 \cdot H_2O$ reactor and Magnetite heat storage). Each technology is designed and sized on slightly different grounds. Hot water tanks and oil thermal storage tanks are typically sized for DHW delivery only; however the others can serve the space heating demands via a wet system as well. Notably, oil thermal storage tanks can also supply heat for cooking.

Installation into existing systems would require some technology specific control for all, with hot water tanks, PCM in storage tanks and Sunamp heat batteries suitable for retrofit alongside existing heat generation and delivery technologies. Oil thermal storage tanks, $SrBr_2 \cdot H_2O$ reactor and Magnetite heat storage are all pilot systems, so installation is not set, however they would each require different degrees of reconfiguration to incorporate. Oil thermal storage tanks would need a new pipe network to deliver full functionality.

Further, oil thermal storage tanks, $SrBr_2 \cdot H_2O$ reactor and Magnetite heat storage are not yet market-ready products. They each demonstrate exceptional performance; oil thermal storage tanks enabling cooking heat delivery all from solar, $SrBr_2 \cdot H_2O$ reactor boasting best-in-class thermal storage density (kWh/m^3), but require significant operational challenges be overcome before a domestic ready product is available.

On a cost basis, of the configurations reviewed, and based on the available data in 2017, PCM in storage tanks (£102/kWh) was most cost effective, then hot water tank (£162/kWh) and Sunamp heat batteries (£340/kWh). Each of these technologies was more economical than the seasonal storage alternatives.

3.3.2.2 Seasonal storage (HS05, HS07, HS08, HS09, HS10)

Seasonal heat storage technologies are commonly embedded underground due to the significant volumes (>5,000m^3) required to avoid excessive heat loss during inter-seasonal storage. Sunamp boasts seasonal storage capabilities but the heat loss rates quoted would suggest very poor round-trip (charge-discharge) efficiency. Seasonal heat storage is effective at bridging the gap between peak solar generation and heat demand. They can be used to bridge between smaller generation/demand gaps, however other technologies (hot water tank) can cover diurnal demand shifting needs for lower cost.

Large underground stores (aquifers to pools) are effective at storing heat at moderate temperature, and therefore tend to require coupled heat pumps and a buffer tank to meet higher temperature

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demands for hot water. Further, specific underground geological formations are required for aquifer and borehole thermal storage applications. Due to the high investment costs (£7,000 to £250,000+), systems are installed at a community scale, servicing multiple 100s of properties with the necessary plant equipment to deliver. For example, a block of flats solution, with a low-temperature heat network, powered by multiple boreholes, could have individual small 2kW heat pumps per property to transfer heat into the flats.

Complex control, additional plant, significant design and capital costs are required, however the benefit of maximising the use of solar heating, and a free renewable heating source, provides significant advantages for communities of social dwellings where the system can be installed and operated by a housing association, local authority or other social landlord (e.g. aquifers may cost around £3/kWh). Pit/tank thermal storage does not require specific geological conditions for installation, however requires significant site area; borehole thermal storage is a more space saving seasonal storage technology. $SrBr_2 \cdot H_2O$ reactor or equivalent technologies will likely revolutionise seasonal thermal storage with transportable media; however these are still at the research and development stages.

3.3.3 Cooling technologies

Although many of the technologies normally used for cooling could be used to store energy for space heating, they cannot provide high grade heat for hot water. Further, without storing heat in summer and discharging in winter, there is negligible saving in energy use for domestic space heating. The problem is that they discharge mid-season or on mild days, when there is minimal benefit.

Further, some of these (like exposed concrete) actually require more heating energy to bring them up to temperature at the start of the heating season or heating period. This means that these technologies alone will not provide the thermal storage required for integrated electrical heating. They have therefore been omitted.

Table 6 - Summary of cooling technologies

Ref#	Technologies	Description	Scale	Application
C01	PCM wall board / insulants	Wall- or ceiling- integrated panels: DuPont - Energain, Knauf - Comfort board	Room by room	Passive thermal mass - applied to building fabric to offer enhanced thermal storage and tempering of space heating
C02	Micronal plaster	Made by Microtek: <500 micro meter diameter capsules, filled with PCM, mixed into plaster mixes up to 20%	Room by room	Passive thermal mass - applied to building fabric to offer enhanced thermal storage and tempering of space heating. Primarily intended to prevent overheating.
C03	PCM mounted tubes	PCM product-filled plastic tubes, mounted on building surfaces	Room by room	Passive thermal mass - applied to building fabric to offer enhanced thermal storage and tempering of space heating
C04	Exposed concrete	Concrete soffits exposed to improve heat transfer between	Room by room	Passive thermal mass - applied to building fabric to offer enhanced

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Ref#	Technologies	Description	Scale	Application
		room and slab, utilising thermal mass		thermal storage and tempering of space heating
C05	Bricks, blocks and mortar	Traditional building materials and building fabric, if suitably insulated can be used passively or actively to temper room air	Room by room	Passive thermal mass - applied to building fabric to offer enhanced thermal storage and tempering of space heating / Active thermal mass - tempering inlet air or water to reducing heating load
C06	Monodraught cool-phase	An alternative to air conditioning - inlet fans force air over PCM thermal batteries that temper the inlet air. Night purging or heating is required during periods of extended extreme weather	Room by room, whole house	Active thermal mass - tempering inlet air or water to reducing heating load
C07	Actimass Podcooler	An alternative to air conditioning - inlet fans force air over PCM thermal batteries that temper the inlet air. Night purging or heating is required during periods of extended extreme weather	Room by room	Active thermal mass - tempering inlet air or water to reducing heating load

3.4 Compatibility matrix

After reviewing all the technologies, four systems have been identified with leading capabilities to use different renewable heating sources and/or cost-efficiently deliver the required heating. The leading technologies have been assessed for compatibility against a range of heating sources (Table 7) and heat delivery mechanisms (Table 8). A scale of 1 (incompatible) to 5 (purpose-designed) has been applied in each case, and colour coded for ease of review.

The technologies considered, and their justification for inclusion, are displayed below.

- HS04: PCM storage tanks – either Sunamp or customised, to deliver hot water in a small volume tank, heated by heat pump or solar thermal.
- HS05: Thermochemical system – included due to potential for sector, likely to emerge as a disruptive technology, able to store stably for extended periods and deliver heat rapidly as required. May need a buffer tank until system designs are refined.
- HS09: Seasonal storage pit – using free solar thermal to supplement other systems through winter.
- HS12: Electric storage heaters – leading cost effective and widely applicable technology for space heating, powered by excess solar PV and Economy 7 (cheap rate electricity overnight).

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Table 7 - Heating source compatibility matrix

Key	Purpose-designed	Compatible	Compatible with some adjustment	May become compatible	Incompatible
Colour	5	4	3	2	1

Heating source	**HS01: DHW cylinder**	**HS03/04: PCM storage**	**HS05: Thermo-chemical**	**HS09: Pit storage**	**HS12: Storage heater**
ASHP generation	4	5	2	4	2
GSHP generation	4	5	2	5	2
District heating	4	4	2	4	2
Solar thermal	4	4	2	5	2
Electrical heating element	5	2	2	3	5
Point-of-use water heaters (e.g. electrical showers)	1	1	1	1	1
Gas boilers	5	3	2	3	2
Biomass boiler	4	3	2	3	2
Back boiler	4	3	2	3	2
Excess PV	4	2	2	3	4
Tri-gen (Fuel Cells)	3	3	2	3	2
Micro-CHP	3	3	5	3	2

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Table 8 - Heating delivery compatibility matrix

Key	Purpose-designed	Compatible	Compatible with some adjustment	May become compatible	Incompatible
Colour	5	4	3	2	1

Space heating / DHW system	HS01: DHW cylinder	HS03/04: PCM storage	HS05: Thermo-chemical	HS09: Pit storage	HS12: Storage heater
Hot air system	2	2	2	2	5
High temperature wet radiator (60°C+)	3	4	5	3	2
Low temperature wet radiator (40-50°C+)	3	4	4	3	2
Wet under floor heating	3	4	4	3	2
Electrical underfloor heating	1	1	1	1	1
Electrical storage heaters	1	1	1	1	5
Wet storage heaters	4	4	4	3	2
DHW	5	5	5	3	2
Point-of-use water heaters (e.g. electrical showers)	1	1	1	1	3

3.5 Performance against hot water cylinder

The heat storage technologies reviewed offer differing benefits and drawbacks against traditional DHW storage tanks. Primarily, DHW storage tanks (HS01) benefit from a highly established supply chain, with a broad network of knowledgeable installers and service engineers. They are relatively low cost and have been purposely designed to meet DHW demand.

PCM storage systems (HS04) benefit from reduced storage volumes, whilst maintaining relatively similar operation, which minimises the need for industry to retrain. They would approximately

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double the cost of installation, and would require new control systems, but they can be readily installed into compact domestic storage locations, e.g. under the stairs or in a kitchen cabinet.

Thermochemical technologies are most likely to significantly disrupt the heat storage market when commercial offerings are available. The pilot reactor system reviewed (HS05) has been configured to deliver DHW, wet heating and seasonal storage functionality – combining the benefits of HS01 and HS09 in one novel solution. Significant research is required to determine optimum reagents and operating conditions. Against HS01, HS05 could store the same amount of heat in just one tenth of the volume.

Pit storage (HS09) betters HS01 by offering seasonal storage. This is highly beneficial for communities with large amounts of excess solar thermal heat. The drawbacks lie in the additional space requirement, both for the pit storage tank, and the additional system equipment required, such as a buffer tank held at DHW temperature to meet instantaneous demand, and heat pump to raise the water temperature. Finally, these systems have high capital costs, as much as a thousand times more than a DHW tank, but can be the most cost effective (£2/kWh) form of heat storage due to their large capacities and free source of heat. For this reason they are suitable for large capital projects by social housing providers.

Storage heaters (HS12) can be an effective accompaniment to an immersion heated DHW storage tank since the two serve different domestic heat requirements. Storage heaters offer the highest thermal storage density (up to 159 kWh/m^3) due to the very high temperatures that the ceramic storage materials can withstand. Modern storage heaters have also overcome previous design flaws with improved insulation and 'fan boost' settings, enabling space heating to meet occupancy demands. They are relatively low cost systems, versatile, able to link to any system as a secondary back-up space heating technology, and have an established supply chain. Their drawbacks lie in their inability to provide hot water. This can be overcome with point-of-use heaters or an immersion heated buffer tank, both of which though require high-peak power.

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4 Emerging trends

This section provides a commentary of elements in the industry and research that are trending, what to watch for, and how this will affect the provision of low carbon heat.

The landscape review thus far has looked at the materials and technologies available, at least at a pilot stage. Reviewing the academic and industrial landscape a number of trends have been identified that are likely to strongly influence the trajectory of the domestic heat storage market. Different trends favour different forms of storage, which affects the likely merits of each technology for integrated electric heating.

4.1.1 Sector trends

The long established evidence that the 'fabric first' approach is the most effective method for reducing heating demand is gaining traction in construction, particularly retrofit. The approach recommends improving the insulating characteristics of the building thermal envelope (walls, doors, windows, roofs, etc.) before replacing or upgrading any heat generation (e.g. boilers) or delivery technologies (e.g. radiators).

This trend is particularly clear in the emerging deep retrofit market, with approaches from various providers seeking to lower space heating demand from c.140 $kWh/m^2/year$ to 30 $kWh/m^2/year$. In doing so the approach alone reduces the carbon intensity of the old heating technology by over 75%.

Further, the distributed heat generation market is growing; be it through self-generation technologies such as ASHPs, micro-CHP or solar thermal arrays, or through local community-generation through geothermal arrays, biomass or CHP powered heat networks. Much of this has been stimulated through the government's Renewable Heat Incentive (RHI) scheme. The RHI payments are continuing to fall, however the move to low-carbon heating is continuing.

Similarly, PV installations continue, despite reducing FIT (feed-in-tariff) payments. With the FIT decline, more homeowners are looking to increase their self-consumption (the amount of energy generated that is used on site). With falling prices of both electrochemical batteries and thermal storage technologies, their increasing longevity and energy density could make them cost effective ways to satisfy this demand.

Finally, the move towards community solutions has encouraged heat networks, the lowest carbon solutions using large high temperature heat stores to switch off heat generating technologies (e.g. GSHPs) when grid power is most constrained, or balancing summer excess heat generation from CHP powered heat networks to meet winter demand. Further, novel solutions are exploring low temperature thermal storage through low temperature heat networks connected to low power individual heat pumps for each flat in a block.

4.1.2 Research trends

From an academic and industrial research perspective, trends have emerged from fundamental material development, through to enhancement of the most fundamental building blocks, to

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improve thermal energy storage. DECC's Smart Heat programme stimulated a tranche in industrial/academic innovation, alongside various Innovate UK programmes. A number of these part-funded technologies have begun to emerge on the UK market, with further innovations likely to follow over the coming years.

From a materials perspective, PCM research continues to focus on additives to overcome poor thermal conductivity or flammability (all the more important post Grenfell Tower). Encapsulation methods are often cited. Industrial innovation has focused on bio-based PCMs, which are less flammable or corrosive and can be disposed of naturally.

Thermochemical research is receiving the most attention at present, with funding granted for material and chemical pathway research through to optimising operating conditions and system configuration for various applications.

In addition, research attention is also focused on optimising the control and management of community thermal storage networks. Here machine learning algorithms are being applied to optimise a neighbourhood's low-carbon supply, storage and demand.

From the continued investment in the area, innovation will continue to produce novel materials, control networks and delivery technologies to meet the reduced thermal demand.

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5 Summary and closing remarks

5.1 Summary

This report and the accompanying Technology Matrix examine 13 heat storage technologies and seven cooling technologies. It compares the heat storage technologies against different heat sources and ways of providing space heating and hot water in homes, with ratings for each against their suitability.

The report puts forward four technologies that merit further consideration in the Integrated Electric Heating project:

1. Phase-change materials in a storage tank – using the Sunamp system or another system to provide storage over a day or a few days.
2. A seasonal storage pit – using solar thermal energy to store energy from summer to winter.
3. Electric storage heaters – powered by excess solar PV and cheap Economy 7 electricity overnight.
4. A thermochemical system – included for its potential as a disruptive technology, which may need a buffer tank until system designs are refined.

5.2 Recommendations

Building characteristics will determine the preferred heat storage system for each given application. These characteristics include the available heat sources, building usage patterns and insulation. Secondly, system characteristics such as system cost and ability to install/maintain will determine the preferred solution for each given source.

The following recommendations are based on the retrofitted UK average house outlined in Section 2.4 above, assuming no access to communal heat networks.

The ideal solution depends on the specific needs of the household. In many cases a combined approach will be most effective at utilising the different renewable heat sources available. The below are the front running technologies:

- HS12: Electric storage heaters – leading cost effective and widely applicable technology for space heating, powered by excess solar PV and Economy 7
- HS03 or HS04: PCM storage tanks – either Sunamp or customised, to deliver DHW in a smaller volume tank, heated by heat pump or solar thermal
- HS09: Seasonal storage Pit – using free solar thermal and supplement systems through winter
- HS05: Thermochemical system – will emerge as front runner, able to store stably for extended periods and deliver rapid heat as required. It may need a buffer tank until system designs are refined.

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7 Appendix

7.1 Comparative analysis parameters

Parameter	Content descriptor or units
Ref#	*Technology reference number*
Technologies	*Name / brief description*
Description	*Verbal description*
Scale	*Category: Room by room, Domestic home, community, country or country scale*
Application	*Hot water (in)direct, passive thermal mass, seasonal storage application*
Container	*Tank, blocks, etc.*
Picture of technology	*N/A*
Picture caption	*text*
Technology Readiness Level	*1 (unproven concept) - 9 (commercial ready)*
Ease of installation	*1 (complex) to 5 (easy, i.e. DIY)*
Familiarity within installation industry	*1 (low) to 5 (high)*
Complexity of control	*1(complex) to 5 (passive)*
Controllability (sensitivity and responsiveness)	*1 (limited) to 5 (highly responsive)*
Applicable storage period	*1 (less than a day) - 5 (seasonal)*
Operating temperature range	*°C (Inlet, Storage and Outlet temperatures)*
Maintenance requirements	*1 (high levels) - 5 (low levels)*
Longevity	*years*
Energy source	*e.g. Electricity, Solar radiation, Heat conduction, fossil fuel*
Delivered energy form	*(in)direct Hot water, (in)direct hot air*
Indicative size/space requirement (or range)	*(m^3)*
height x depth x width or height x diameter	*(mm)*
% space requirement of water tank	*(%)*
Specific heat capacity at operating temperature (65°C for comparison)	*(kJ/kgK)*
METHOD: Total heat density over operating range (10°C ΔT for comparison)	*(kJ /m^3)*
Total heat density over operating range (10°C ΔT for comparison)	*kWh/m^3*
Thermal storage capacity (or range) of commercial offering	*(kWh_{th}) (assuming perfect insulation for comparison)*
Cost of material	*(£/kWh)*
Cost of whole system (container unit, insulation, control and heat storage medium)	*(£) and (£/kWh)*
Storage efficiency	*(%)*
Installation costs	*(£) or (£ - 10s to ££££ - 100,000s)*
Volume for 2.2kWh(th)	*m^3*

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Volume comparison with hot water tank	*% of water tank, based on storing the same amount of thermal energy*
Upstream compatibility	*heat generation*
Downstream compatibility	*heat delivery*
Health and safety risk	*(e.g. Fire risk, Toxicity risk for occupants, etc.)*
Resource availability (procuring, disposal, etc.)	*commentary*

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