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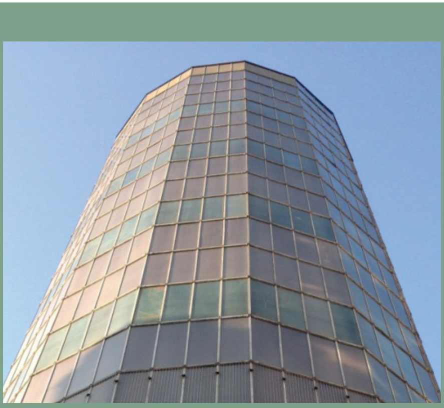

The Future Role of Thermal Energy Storage in the UK Energy System: An Assessment of the Technical Feasibility and Factors Influencing Adoption

Research Report

The Future Role of Thermal Energy Storage in the UK Energy System: An assessment of the Technical Feasibility and Factors Influencing Adoption

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Executive Summary

The aims of the work undertaken were:

- To characterise the main areas of heat use in the UK and the magnitude of the primary energy used
- To describe the main characteristics of the different technologies and approaches available for thermal energy storage and provide examples of their availability, deployment and demonstration
- To review current thermal energy storage system research to determine key characteristics, costs, maturity and additional research requirements
- To identify key application areas for thermal energy storage in the UK based on a national target for an 80% reduction in greenhouse gas emissions by 2050
- When combined with large scale deployment of electric air source heat pumps, to explore the potential for peak grid load balancing and the magnitude of thermal energy storage that could be achieved on a distributed basis

Key findings

Just under half (45-47%) of total final energy consumption in the UK is currently used for heating purposes with approximately 80% derived from fossil fuels. Of the total national heat demand, space and water heating account for 63% and 14%, respectively. The domestic sector is responsible for 57% of total heat use with 77.5% being for space heating. Of the 18% of heat supplied for industrial processes, 6% is for high temperature process, 9% for low temperature process and 3% for drying and separation. Due to the large seasonal variation in space heating requirements, the annual heat load profile is far from constant, with the peak winter heat load being several times that of the average heat load.

At present, sensible heat storage is by far the most utilised and mature form of heat storage system, with most current thermal energy storage installations being based on this approach. Store volumes range in size from domestic hot water tanks and electric storage radiators designed to store heat for a few hours to systems with volumes up to 75,000 m3 used for inter seasonal storage. Latent heat and thermochemical heat storage systems, although potentially providing greater energy storage for a given volume, are still at lower technology readiness levels.

The four main types of large scale, low temperature, thermal energy stores that have been successfully developed are: tank thermal energy stores, pit thermal energy stores, borehole thermal energy stores and aquifer thermal energy stores.

Large inter-seasonal stores are only sized for a maximum of a few hundred buildings. Due to the annual operational cycle, the store cost must be low to provide payback on investment. There is a strong relationship between store size and cost, with small tank storage systems of 300m^3 of water costing about £390/m^3, whilst for a pit store with a volume of 75,000m^3 of water equivalent, costs may reduce to around £25/m^3. The district heating system at Pimlico (one of the systems examined in this project) effectively uses a 2,500m^3 volume water store constructed in the 1950s to provide a short term balancing function for a CHP system supplying 3256 homes, 50 businesses and three schools.

Until such time as the existing building stock is radically transformed to be much more thermally efficient, or replaced with energy efficient new build, the greatest use of heat in the UK is likely to remain that for space heating. To achieve the significant planned reductions in greenhouse gas emissions, low emission heating approaches will be essential. Electric heat pumps operated with a decarbonised electricity supply and district heating can help address this problem. To assess the feasibility of these approaches two case studies have been undertaken, i) for domestic heating using data for a dwelling in Derby and ii) for the Pimlico district heating scheme in London.

In the first case study, daily winter heat requirements and daily peak heat requirements were determined for a large family house in Derby and scaled, based on the predicted performance if the house was compliant with the Building Regulations of 1980, 1990 and 2010. Thermal stores were then sized to meet the maximum space heat load for a three hour period to allow heat pump operation at periods of low electrical grid load. For a water-based sensible heat store, the storage volumes required were found to range from 2.6m^3 for the house constructed to 1980s Building Regulations, to 0.56m^3 for construction to 2010 Building Regulations. A "theoretical" phase change material (PCM) based store could reduce these volumes by two thirds. Given that PCM storage is likely to become a viable technology in the next few years, PCM-based thermal storage in conjunction with an electric air-source heat pump, offered as part of a Green Deal, was examined and found to be technically possible in a retrofit context. If operated in conjunction with an appropriate demand side management strategy, this type of system has the potential to support domestic energy demand reduction while at the same time minimising supply challenges for the electricity utilities.

In the second case study, an analysis was undertaken of the Pimlico District Heating Undertaking which includes a 2500m^3 thermal store built in the 1950s. The thermal energy store provides a balancing function to match variable supply and demand and also offers an emergency buffer to ensure seamless supply in the event of planned or unexpected maintenance. The thermal store at Pimlico District Heating Undertaking allows better control and plant efficiency; without the thermal store, the system would need to vary in operation to meet the changing demand, and so run inefficiently.

An analysis was undertaken of the potential additional national electrical generation and peak grid load resulting from the deployment of different numbers of air source heat pumps with different performance characteristics. In addition the potential storage in GWh of heat and electric equivalent that could be achieved with distributed thermal storage was calculated. For example, two million air source heat pumps with a winter COP of 2, each meeting a 12kW thermal load, would require an extra 12GW of electrical generation (compared to a current winter peak load of just under 60GW). If each dwelling equipped with a heat pump system had three hours of thermal storage, i.e. 36kWh to enable demand shifting, then the equivalent electrical storage would be 36GWh. This would enable improved capacity factors of generation plant to be realised and have the potential to reduce the amount of additional power generation capacity that would be required to meet this additional load.

Provision of heat in the transition to a low carbon economy is a significant challenge. Heat networks currently supply less than 2% of the UK's space heating compared to approximately 16% in Germany. Heat networks allow large scale storage systems to be used that provide efficient storage and effective load shifting capability; expansion of heat networks in the UK is possible in areas of high heat demand although cost of installations is high at present. If the electricity supply is decarbonised, combined heat and power will no longer be the lowest carbon option and large MW-scale heat pumps may prove preferential.

The wide-scale adoption of air source heat pumps for space heating will require significant investments due to the seasonal variation and magnitude of peak winter loads. Strengthening of the low voltage electrical network and significant additional generation capacity will be needed in addition to major building refurbishment to reduce heat loads. Distributed thermal energy storage can provide a significant load shifting capability on a diurnal basis. However, without the development of effective latent or thermochemical heat storage systems, the storage volumes required will be large and difficult to integrate into existing domestic dwellings.

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Glossary

Absorption	Process by which one substance, such as a solid or liquid, takes up another substance, such as a liquid or gas, through minute pores or spaces between its molecules.
Adsorption	Accumulation of gases, liquids, or solutes on the surface of a solid or liquid.
Aquifer	Rock formation that allows water to move through it. The aquifer must occur above a layer that prevents the water seeping away, such as clay. In an aquifer deep below the surface the water will be hot.
Carbon capture and storage (CCS)	Capture and long-term storage of carbon dioxide as it is released into the atmosphere from fossil fuels either before or after combustion.
Charge / discharge cycle	Process of repeatedly charging and discharging heat from a thermal store.
Coefficient of Performance (COP)	Ratio of useful energy output to required energy input.
Combined heat and power (CHP)	System to utilise heat from electricity generation, thus providing both heat and power.
Coolth storage	Storing materials at low temperature to provide cooling at a later time.
Decarbonised supply	Supply of energy where the carbon has been removed from its production process.
Deep retrofit	Process of retrofitting energy efficient technologies to buildings at a whole property level to achieve significant reductions in energy demand.
District heating	Supply of heat and/or hot water from one source to a district or a group of buildings.
Energy Density	Amount of energy above a specified datum condition stored per unit mass within a system.
Enthalphy	Thermodynamic quantity equivalent to the total heat content of a system. It is equal to the internal energy of the system plus the product of pressure and volume.
Eutectic mixtures	Mixture of substances (in fixed proportions) that melts and freezes at a single temperature that is lower than the melting points of the separate constituents or of any other mixture of them.

Green Deal	UK government policy to permit loans for energy saving measures for properties in Great Britain.
Heat loss coefficient "U"	Measure of the ability of a material or component to transfer heat per unit time, per unit area per degree temperature difference across the material or component.
Ice slurry	Mixture of solid ice particles in a fluid forming a suspension with two phases.
Interseasonal storage	Storage of heat or cold for periods of several months.
Latent heat	Heat required to convert a solid into a liquid or vapour, or a liquid into a vapour, at constant temperature.
Load shifting	Process of moving electrical or heat demand from peak times to off-peak times.
Packed bed systems	Contained volume filled with a packing material through which a heat transfer fluid flows.
Peak demand	Maximum electricity demand for an electricity supply system or the maximum heat demand for an heat supply system.
Phase change material (PCM)	Substance that undergoes a change of phase at a set temperature generally with the release or absorption of a large amount of energy.
Sensible heat	Heat exchanged by a body or thermodynamic system that has, as its sole effect, a change of temperature.
Solar thermal collector	Device for intercepting and converting solar energy into thermal energy.
Solar thermal system	System comprised of solar thermal collectors and other system components, for example a thermal store.
Steady-state model	Mathematical model of a system where conditions are assumed to be time-invariant, i.e. independent of time.
Thermal accumulator	Store of thermal energy for the purpose of allowing variable thermal loads to be met by constant or variable thermal generation and for the prevention of interruptions in supply.
Thermal resistance	The resistance to heat flow offered by a material, expressed as thickness of the material divided by the thermal conductivity of that material. Can also be defined to account for resistance to convective and radiative heat flow.
Thermal stratification	Stratification based on temperature.
Thermochemical heat	Heat produced as a result of a chemical reaction.

Introduction

1

Just under half of total final energy consumption in the UK is currently used for heating purposes with approximately 80% derived from fossil fuels. Without a significant drive to decarbonise heat production, it will not be possible to achieve the UK government's target of 80% reduction in greenhouse gas emissions by 2050. Of the total national heat demand, space and water heating account for 63% and 14% respectively. Space heating demand is strongly dependant on outdoor weather conditions, with large summer to winter variations and significant diurnal variations depending on building occupancy also likely to occur. The variable nature of heat demand, with load profiles that are, to an extent, predictable, presents opportunities to use thermal energy storage to manage supply requirements to meet a specified demand.

This report presents the findings of an 18-month UKERC research project into the potential role that could be played by thermal energy storage within the UK energy system. The investigation includes an assessment of technical feasibility, as well as the factors that could influence adoption.

The aims of the work undertaken were:

- To characterise the main areas of heat use in the UK and the magnitude of the primary energy used.
- To describe the main characteristics of the different technologies and approaches available for thermal energy storage and provide examples of availability, their deployment and demonstration.
- To review current thermal energy storage system research to determine key characteristics, costs if available, maturity of technology and any additional research requirements necessary to move systems to demonstration and deployment.
- To identify key application areas for thermal energy storage in the UK, in particular those that may have a major role in enabling a significant reduction in the greenhouse gas emissions associated with heat provision.
- When combined with large scale deployment of electric air source heat pumps to identify the potential for peak grid load balancing and the magnitude of thermal energy storage that could be achieved on a distributed basis.

The report is structured as follows:

Chapter 2 presents an analysis of the total final energy use in the UK for heating purposes. It presents the data in terms of sector, application and fuel source. Space heating and water heating are further analysed due to their magnitude.

Chapter 3 introduces the different thermal energy storage approaches (sensible, latent and thermochemical) , provides examples of currently installed systems and presents details of technology status and the main research and development topics at the present time.

Chapter 4 presents a case study analysis of the heat loads for a domestic family dwelling in Derby assuming that it complies with Building Regulations for the 1980s, 1990s and 2010s. The thermal energy storage capacity required to displace the peak diurnal winter day space heating load by 3 hours for compliance with each set of building regulations was analysed, and storage size was calculated based on a hot water store and a phase change material store.

Chapter 5 explores the non-technical barriers to UK deployment of thermal energy storage through a case study of the Pimlico District Heating Undertaking. Benefits that the store provides to the system operation and its customers are identified, and possible issues with a skills gap in deploying a large number of similar systems are identified.

Chapter 6 examines two approaches that can be used to provide low carbon space heating, namely electric air source heat pumps and district heating systems. The levels of storage that would be required for 3 hours load shifting are evaluated for a range of system and load assumptions and the equivalence to electrical energy storage calculated.

Chapter 7 briefly details the main conclusions derived from this work.

The Current Demand for Heat in the UK

2

In 2011 45% of total final energy consumption in the UK was for heating purposes, initial figures for 2012 indicate an increase to 47% due primarily to colder winter weather [1]. In the UK in 2011 the total final energy consumption excluding non energy use of fuels was 202.1 million tonnes of oil equivalent (mtoe), increasing to 206.3 mtoe in 2012 [1]. Figures 1 to 10 are based on data published by DECC [1]. From Figure 1 it is clear that heat use is the single largest component of total final energy consumption. Cooling, ventilation and refrigeration are included in other energy use and are (based on the data in [1]) responsible for slightly less than 1% of total final energy consumption.

Figure 2 presents the breakdown of heat use by sector. It can be seen that the domestic sector is responsible for 57% of the heat use, with industry slightly higher at 24% than the service sector at 19%.

An alternative breakdown of heat use by purpose over the three sectors is presented in Figure 3. In the UK, space and water heating combined are responsible for 77% of the total final energy consumption used for heat, or approximately 36% of all total final energy consumption.

High temperature process heat, low temperature process heat and drying and separation are all linked to the industry sector, and combined represent 18% of the total final energy consumption used for heat. Considering the time varying quality of the loads, all heat loads except space heating, (that is 37% of the total) are likely to be similar throughout the year. Space heating will however have significant variation throughout the year, being minimal in the summer period, with the majority load in winter, with smaller loads in spring and autumn. The climate determines the space heating load profile with colder weather resulting in increased energy use.

The dominance of gas in the provision of heat can be seen from Figure 4, with all other fuel sources only contributing 29% when combined. Electricity at 15% is the second largest fuel used for generating heat. The breakdown of the electrical energy for heat use is 42% for space heating purposes, 10% for water heating, 17% for cooking and catering and the remainder for process heat and drying and separation in industry.

Figure 1. Energy Consumption by End Use, 2012

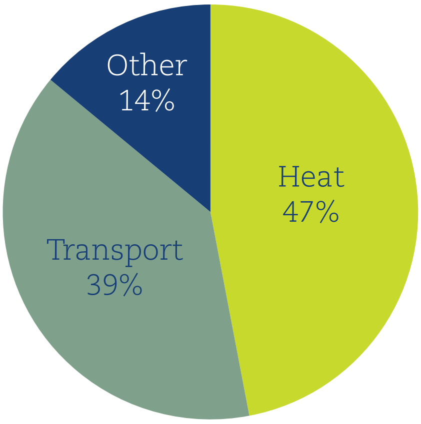


Figure 2. Heat Use by Sector, 2012

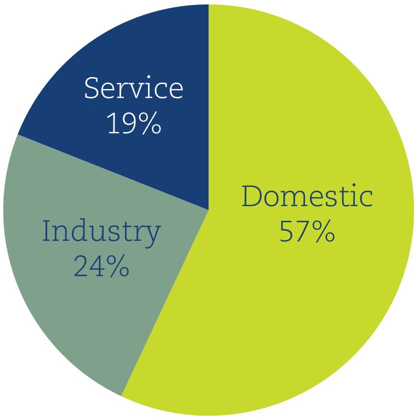


Figure 3. Heat Use by Purpose, 2012

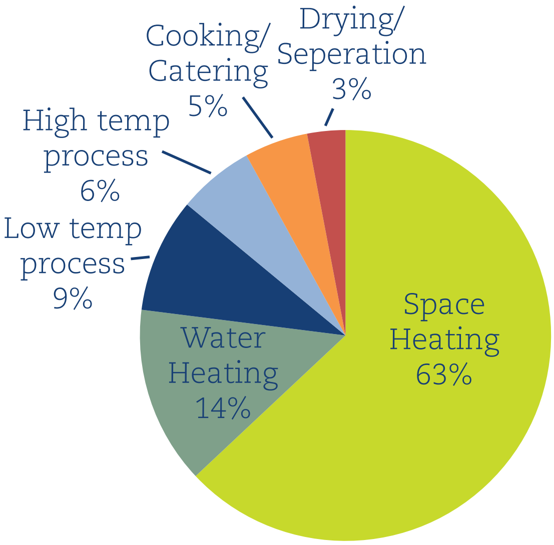


Figure 4. Breakdown by Fuel of Total Heat Use, 2012

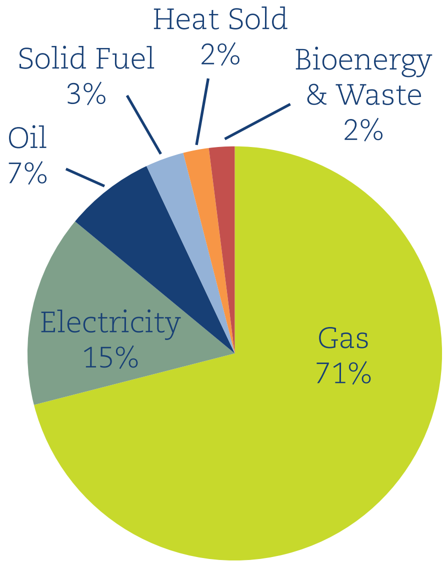
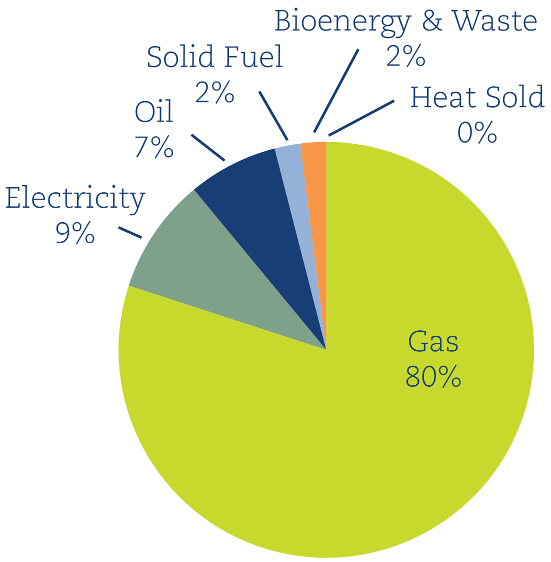


Figure 5. Breakdown by Fuel of Domestic Heat Use, 2012



Solid fuel and oil combined provide 10% of the energy consumption for heat. Gas, oil and solid fuel provide 81% of the total fuel for the consumption of heat.

Figure 5 presents the breakdown of fuel for domestic heat use which, from Figure 2, is 57% of the total. It is clear that gas is an even larger energy supplier to this sector with 80% of energy consumption for heat coming from this source, electricity at 9% is the second largest source of energy providing the same as solid fuel and oil combined. Gas, oil and solid fuel provide 89% of the total fuel for the domestic consumption of heat.

Breaking down the data further and considering space and water heating separately it can be seen from Figure 6 that for space heating (which is 77.5% of the total heat use in the domestic sector) the breakdown is similar to the total domestic breakdown except that electricity reduces by 1% to 8% and oil increases by 1% to 8%. It is important to note that domestic space heating is 44% of the total energy consumption for heat and will have both significant variation with season and also significant variation within a 24 hour period depending on occupancy. Gas, oil and coal provide 90% of the energy consumption for space heating in the domestic sector.

Figure 6. Breakdown by Fuel of Domestic Space Heating, 2012

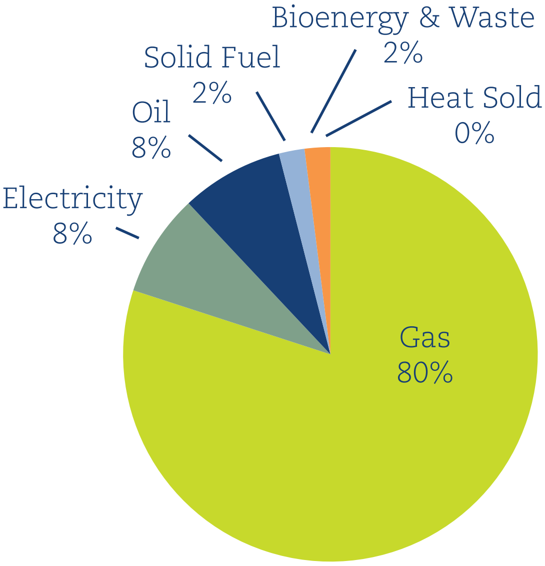


Figure 7. Breakdown by Fuel of Domestic Heat Use, 2012

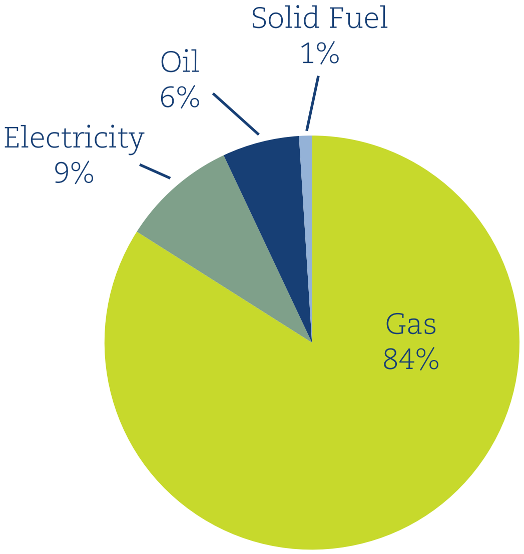


Figure 7 presents the breakdown by fuel use for domestic water heating (which is 19.5% of the total heat use in the domestic sector), gas provides 84% of the total, with electricity at 9%. The domestic water heating demand profile will be more uniform throughout the year when compared to space heating; however it corresponds to only 11% of the total energy consumption for heat. Gas, oil and solid fuel provide 91% of the energy consumption for domestic water heating.

Figure 8 presents the breakdown of all space heating (domestic, industrial and services) by fuel type. Gas makes up slightly less of the total at 74% than for the domestic sector alone, oil and solid fuel providing a further 10%. The space heating loads in the service and industry sectors will have similar seasonal variation in heat load; however, due to the different occupancy patterns the daily heat load profile will be different to that of the domestic sector with an initial peak prior to the start of the working day to achieve comfort conditions with heat input through the working day to maintain the set point temperatures. From Figure 9 it can be seen that the industry and service sector correspond to 30% of the total space heating load.

From the above figures based on the provisional estimates of overall energy consumption for 2012 [1] it is clear that:

- The provision of heat, at 47% of overall energy consumption by end use, is the most significant energy use in the UK
- The domestic sector is responsible for 57% of total heat use, with 77.5% of this being for space heating
- Of the total heat provided 63% is for space heating which will have significantly higher demand in winter than summer
- 37% of heat use will be relatively constant throughout the year (14% for water heating, 5% cooking and catering, 6% high temperature industrial process, 9% low temperature industrial process and 3% drying and separation)
- 77% of total heat supplied is for low temperature applications, i.e. space and water heating
- 18% of heat supplied is for industrial processes
- Gas, oil and solid fuel supplies 81% of the energy consumption for heat.

Figure 8. Space Heating by Fuel Type, 2012

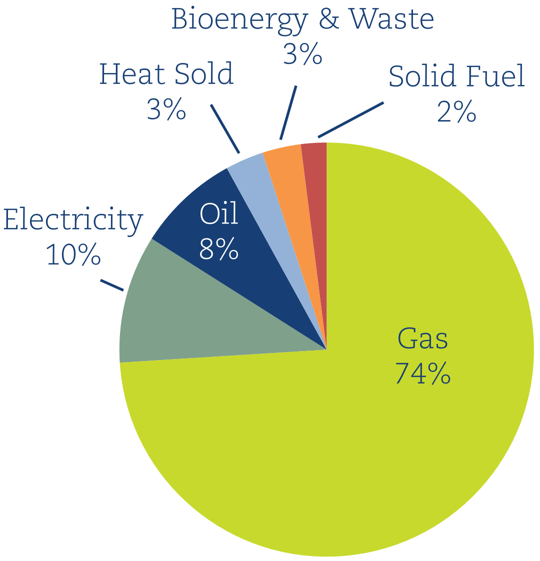


Figure 9. Space Heating by Sector, 2012

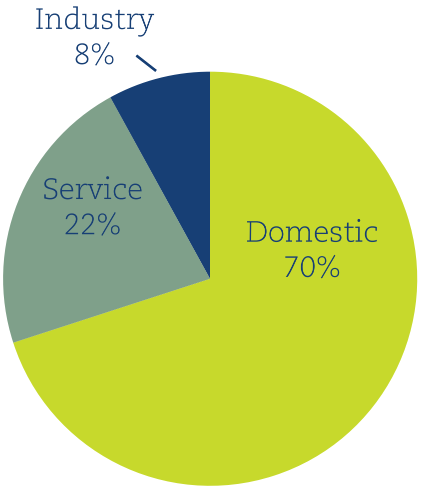
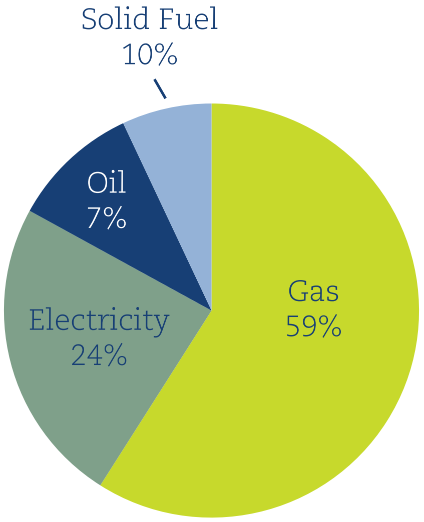


Figure 10. Industrial Heat (excluding space heating) by Fuel Type, 2012



To achieve the UK legally binding target of 80% reduction in CO_2 emissions by 2050 it is essential that the gas, oil and solid fuel used for heating is substantially reduced or substituted by a sustainable energy resource.

The provision of space and water heating (representing 63% and 14% of total heat demand) in a low carbon way is a major challenge. New buildings can be built to have very low heat loads, however existing buildings will form a major part of the building stock in 2030 and 2050. Deep retrofit of buildings to significantly improve performance and reduce heat loads is, to date, progressing at a slower pace than required. For example, the report 'Retrofit Incentives' by the UK Green Building Council [39] states that one home retrofit per minute will be required between now and 2050 for the UK to meet its carbon reduction target. The recently-launched 'Green Deal' is expected to support the retrofit of 14 million homes by 2020, yet by June 2013 only 245 households had so far agreed a Green Deal Plan to finance energy efficiency improvements. The domestic space heating load is therefore likely to remain significant for the foreseeable future.

To achieve a transition to a low carbon fuel supply for space and water heating will require one or a mix of the following:

- A renewable substitution for gas allowing the existing gas supply network to be used
- Transition to electric space and water heating (assuming the electricity generation system is decarbonised)
- Generation of heat locally using a renewable energy supply source

The need for thermal energy storage is likely to be least in the first option since it potentially allows heat to be supplied largely in a similar way to the present. The second option will result in the need for significant increase in generation capacity to meet peak winter loads, with the consequence that in the summer much generation plant will stand idle. It is also probable that significant strengthening of the grid infrastructure will be required. Distributed heat storage sized to meet peak winter loads for two to three hours could significantly reduce the winter peak. The third option, unless biofuel based to provide a robust mechanism for supplying heat on demand, will require longer term heat storage to allow for intermittency; for the case of wind this is likely to be days, for solar thermal, this will need to be seasonal.

Analysis of industrial process heat use documented in [1] reveals that of the 6% of heat used for high temperature processes, three areas use over 90% of the heat: Manufacture of chemicals and chemical products (9%), Manufacture of other non-metallic mineral products (43%) and Manufacture of basic metals (40%). Similarly the three largest users of low temperature heat comprise nearly 56% of the total low temperature heat used, Manufacture of food products (22%), Manufacture of coke and refined petroleum products (21%) and Manufacture of chemicals and chemical products (13%). Drying and separation is distributed through a wider range of industrial sectors, however considering the largest three users (Manufacture of paper and paper products (23%), Manufacture of coke and refined petroleum products (25%), Manufacture of chemicals and chemical products (18%)), 66% of the energy use is accounted for.

The breakdown of fuel use for industrial heat excluding space heat is presented in Figure 10. Significant reductions in industrial energy use have been realised in certain sectors in recent years by improvements in efficiency, in particular the Iron and Steel and Chemicals Industry sectors [1]. Gas, oil and solid fuel comprise 76% of the total industrial heat use excluding space heating.

Industrial heat supply is centred on larger scale units and continuous availability is of great importance. If heat is to be supplied in a decarbonised way, the options are similar to those detailed for space heating, however developments in the area of high energy density thermochemical heat storage may provide an additional option:

- A renewable substitution for gas allowing the existing gas supply network to be used
- Transition to electric process heating (assuming the electricity generation system is decarbonised)
- Generation of heat locally using a renewable energy supply source
- Transport of thermochemical heat storage materials from heat generation plant with carbon capture and storage (CCS) or nuclear heat generator

The second option could benefit from heat storage to reduce peak loads particularly for batch processes or those that require irregular rates of heat input.

The fourth option is proposed on the basis that the major heat loads in industry are concentrated in a few sites which are large but most are probably not large enough to employ CCS technology. Good transport links would enable thermochemical materials charged at fossil heat generators with CCS and nuclear generators to be transported to the industrial site; after recombination they would be returned for reuse. An alternative to using CCS or nuclear is that excess wind that is to be shed could be used to charge thermochemical materials.

Thermal Energy Storage

3

Thermal energy storage can be used to help balance differences between heat/coolth generation and demand requirements with respect to both disparities that occur in time and magnitude. Thermal energy storage can provide several advantages:

- Renewable energy, for example solar thermal although not extensively used in the UK is in countries with similar solar resource, (Denmark for example) collected and stored for use at later times either on a diurnal or interseasonal basis
- By generating and storing heat at periods of low demand and regenerating at periods of high demand, increased capacity can be realised within a given generation system allowing improved capacity factor and reducing low utilisation plant, this allows smaller plant to be used for a given peak load, plant can be operated in the most efficient way with reduced cycling and less part-load operation
- If different tariffs are available at different times of the day, heat generation can be shifted in time to reduce peak demand and take advantage of lower tariffs
- Energy efficiency can be improved by utilising heat/coolth that would have been wasted
- Combined heat and power and district heating schemes can be operated in more effective ways to maximise income
- The effects of interruption in supply can be reduced and system reliability increased

There are a number of challenges to thermal energy storage becoming mainstream in the UK, including:

- Low energy density and thus large volume requirements for heat storage with current sensible heat storage approaches
- Storage system initial costs
- Limited experience of the added benefits that storage can provide
- Difficulties in integration and subsequent optimisation when added to existing heat supply systems
- Conventional gas boiler systems can provide heat rapidly with little need of storage
- The limited time of use tariffs available to domestic customers in the current energy system mean there is little incentive to generate and store heat/coolth for later use and change from existing use patterns
- Consumers may be unhappy about the origins of their heat/coolth, for example if it is generated by a company or industrial process that conflicts with their values

3.1 Thermal Energy Storage Approaches

The three forms of heat storage are sensible, latent and thermochemical heat storage (including adsorption heat storage and reversible chemical reactions). Key technical issues identified for consideration when designing a thermal energy storage system are i) the store operational temperature regime, ii) the required heat storage capacity, iii) the charge/discharge characteristics iv) the required duration of storage, v) the energy storage density, vi) round trip efficiency, vii) part load operation characteristics viii) durability and long term cycle stability ix) materials availability, x) cost, and xi) system integration and control. Other important issues that impact on uptake of thermal storage systems relate to required installation skills, maintenance requirements, user perception of performance and acceptability and environmental impacts and safety requirements. A key parameter in determining a system's economic viability is the number and frequency of charge/discharge cycles, for example inter-seasonal storage costs per kWh will need to be low cost due to the small number of cycles over which the investment can be recouped.

3.2 Sensible Heat Storage

Sensible heat storage is by far the most utilised and mature form of heat storage system at present with most working major thermal energy storage installations based on this approach.

The quantity of heat charged/discharged to a sensible heat storage system can be calculated from the product of the store material's specific heat capacity Cp, density ρ, volume V and the difference between the initial store temperature T1 and the final store temperature T2 shown in equation 1.

$$\frac{\frac{4}{3}\pi r^3 \rho C_p (T_2 - T_1)}{4\pi r^2 U (T_2 - T_1)} = \frac{r\rho C_p}{3U} \qquad \text{(Equation 1)}$$

Sensible heat storage relies on the storage of heat in a solid or liquid with no change of phase or chemical reactions taking place. Materials with high density and specific heat capacity can store larger amounts of heat for a given temperature difference compared to those with low values. Due to their low density, gases are not generally used for sensible heat storage. Materials used include water, concrete, granite, molten salts, heat transfer oils, rock, earth, etc. To charge the store, heat is added from a higher temperature source resulting in a temperature rise in the store. To discharge the store, heat is extracted to a lower temperature sink resulting in a reduction in temperature. For a store of a given material with set density and specific heat capacity, the heat stored scales linearly with both store volume and temperature difference. For constant heat loss coefficient U, energy losses from stores are proportional to the store surface area and temperature difference between the store and the ambient environment. The stored energy is proportional to the temperature between the charged and uncharged state and the store volume. Considering the simple case of a spherical store, the fraction of stored energy to rate of energy loss is:

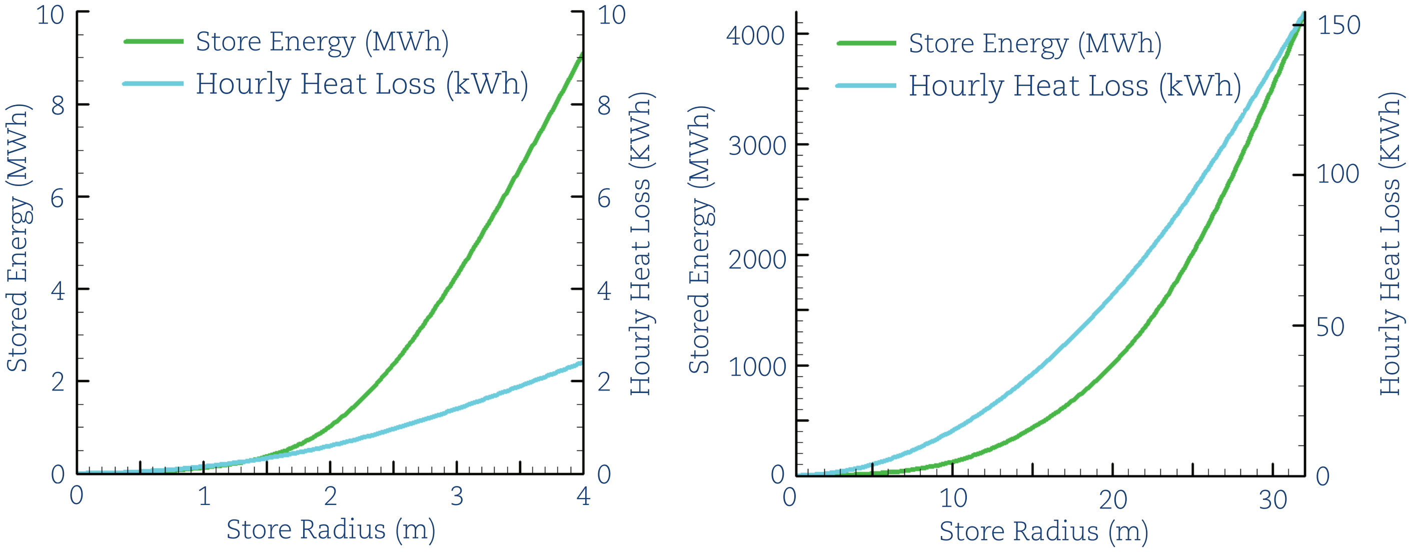
$$Q = \rho V C_p (T_2 - T_1) \qquad \text{(Equation 2)}$$

Increasing the store radius r increases the ratio of stored energy to the rate of losses and explains why very large stores can achieve very low values of percentage energy loss and can effectively store heat over long periods of time.

From equation 2 it can be seen that doubling the store radius (increasing the store volume by a factor of 8) is equivalent to reducing the percentage rate of heat loss by half. This is an important factor when considering the level of insulation to use and the duration of storage required. Small stores need greater levels of insulation to avoid a significant fraction of their stored energy being lost over a short period.

Figure 11 illustrates this relationship graphically for a packed bed heat store using granite as the heat storage material with a void fraction of 10%. The U-value for the store walls is 0.2Wm^{2}k^{-1} and the temperature difference between the charged and discharged states is 60$^{\circ\mathrm{C}}$, similar to that between the store temperature and the ambient temperature. The store is assumed to be fully charged and at a uniform temperature, this temperature difference gives this store a heat storage capacity of approximately 30.5kWhm^{-3}. The heat loss presented in Figure 11 is the heat loss for an hour period assuming that the temperature difference between the store and ambient is a constant 60°C. It is important to note that the energy stored is presented in MWh and the energy lost in an hour in kWh. A 30m radius store corresponds to a volume of approximately 113,000m^{3} which although large, is comparable to the largest underground thermal energy storage systems.

Figure 11. Illustration of the relationship between the Energy Storage Capacity and Heat Loss Rate as a function of store radius for a Spherical Store



When charging and discharging the heat to/from a store based on sensible heat storage in solids the rate achievable is determined by the heat transfer at the liquid/gas-solid interface and the heat transfer within the solid. An important parameter in achieving high powers when using packed bed type systems illustrated in Figure 12 is the surface area to volume ratio of the solid elements. Smaller storage elements with a larger surface area to volume ratio enables both greater rates of heat transfer from the solid to the gas/liquid heat transfer fluid and also reduces the thermal resistance between the centre of the element and the surface enabling more effective charge/discharge; pressure losses within the store are however increased.

Figure 12 shows a matrix of rocks enclosed within an envelope. To charge the store a hot fluid, liquid or gas is introduced at one end of the store. On passing through the store, heat is transferred to the matrix from the gas. This results in a temperature profile/gradient within the store. Counterflow operation to discharge the store enables maximum heating of the fluid to be achieved and more of the heat to be discharged at higher temperatures.

When the heat transfer fluid is contained within a system of pipes, as illustrated in Figure 13, it is essential that the solid storage media is in contact with the external pipe surface. In figure 13, A, illustrates charging, B, illustrates discharging.

To improve performance the flow direction between charging and discharging can be reversed. Heat transfer can be enhanced within larger solid units by introducing elements with higher thermal conductivity. When using a solid material such as concrete with heat transfer tubes inserted through it, to achieve high rates of heat transfer and thus output power, it is important that sufficient surface area for heat transfer is provided. This can be achieved by increasing the number of heat transfer tubes or including fins on the exterior of the tubes, however this leads to increased costs in construction. To reduce temperature gradients in the thermal storage media, higher conductivity materials, for example metal rods, can be introduced.

Liquid thermal energy storage systems can either be of the direct type, where the store fluid and the heat transfer fluid are the same, or indirect type in which the store and heat transfer fluid are separate and a heat exchanger is required within the store. The fluid type used for storage depends on the temperature of application with water, heat transfer oils and molten salts having been used extensively. Thermal stratification within a store is used in some applications since this can provide an advantage in terms of more effective charging and discharging compared to a mixed store and improved operation when part charged.

Figure 12. Schematic of Packed Bed Heat Store: a) Charging and b) Discharging

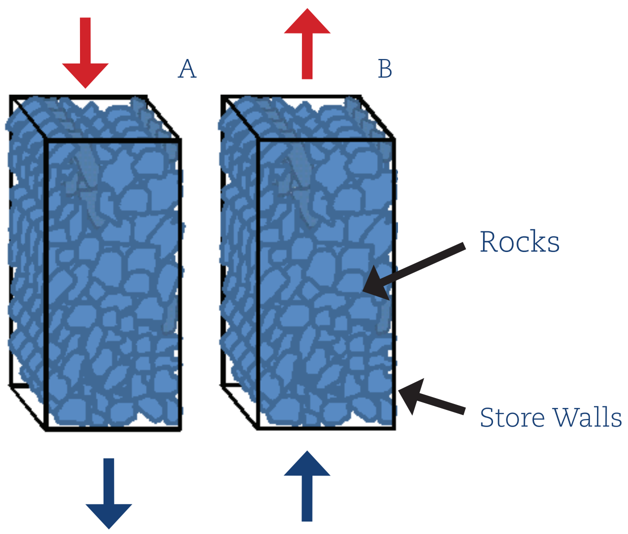
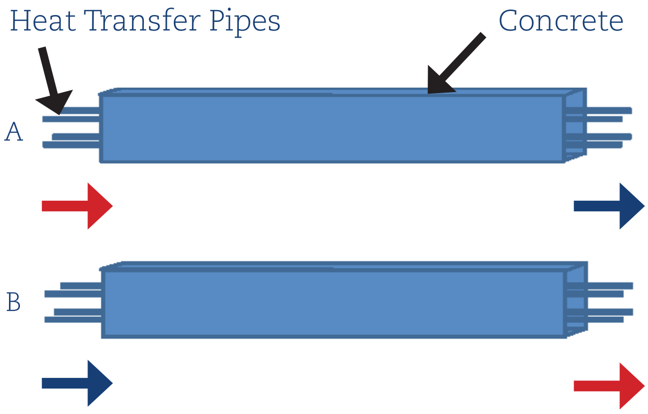


Figure 13. Schematic of Solid Store with Heat Transfer pipes: a) Charging and b) Discharging



The factors that lead to degradation of thermal stratification within liquid thermal energy stores have been extensively studied. They are:

- Mixing of fluid while charging and discharging, this can be reduced by the use of diffusers at the store inlet,
- Conduction within the store walls leading to local temperature gradients that result in mixing of the store fluid, this can be reduced by using a low thermal conductivity wall material or internally insulating the store rather than using external insulation,
- Heat loss from the store walls leading to temperature gradients and mixing,
- Conduction in the store fluid leading to a relaxation of the temperature gradient.

Sensible heat storage systems have been developed that cover a wide range of sizes and applications. The majority of stores that operate in the temperature range between 0 and 100°C are based on water. This is due to the high sensible heat capacity of $1.16kWhm^{-3}K^{-1}$ of water and water's other favourable properties including: cost, abundance, benign nature and extensive previous application.

Small scale thermal energy storage systems may only store a few kWh of heat and are generally used to provide short term buffering over a few hours or to act as a thermal accumulator. A good example of a thermal accumulator is the hot water storage cylinder typically installed in houses, before the increased use of combi boilers sized to provide sufficient hot water to run a bath using a 3kW immersion heater. Using a 3kW immersion heater directly would provide an insufficient heat input to run a bath in a reasonable time. The hot water storage cylinder used with small scale domestic solar thermal systems is another good example of an accumulator allowing heat to be stored when generated during the day from solar input and used at a later time when required.

Due to the small size of the stores it is important that adequate insulation is provided if heat is to be stored for more than a few hours. Vacuum insulated stores have been developed, however the increased system cost may not be acceptable for most installations. Another example from the built environment is the well-known electric storage heater developed to allow off peak night time electricity to provide daytime heating. It employs ceramic blocks heated to temperatures of up to 600°C to store heat, the high temperature of storage enables a significant amount of heat to be stored in a compact volume.

3.3 Large Scale Sensible Heat Stores

Large scale low temperature (<100°C) thermal energy storage systems have been designed to either:

- Provide a short term balancing function when used with Combined Heat and Power and district heating systems with time shifting of heat for periods covering a few hours [2]
- For longer term inter-seasonal storage when using solar thermal systems, provide a significant part of winter heat load [3].

3.3.1 Inter-seasonal Storage Systems

Inter-seasonal storage systems have attracted significant attention in several countries. They are generally either based on solar thermal systems or waste heat and have been implemented for individual dwellings, multi occupancy buildings or for groups of buildings. Many systems are used in conjunction with heat pumps to provide increased delivery temperatures with high heat pump coefficient of performance (COP).

There are four main categories of large scale low temperature thermal energy stores that have been successfully utilised over a number of different sites [4]:

- Tank thermal energy stores
- Pit thermal energy stores
- Borehole thermal energy stores
- Aquifer thermal energy stores

In tank thermal energy stores (TTES), water is the heat storage medium. An insulated water tight envelope is required with sufficient strength to withstand the stresses imposed by the weight of the water. Partial burial underground can help alleviate this problem. To promote effective thermal stratification within the store requires sufficient height, however this must be balanced against the stresses within the store and the surface area/volume ratio and heat losses. Diffusers are usually employed to reduce mixing within the store. The energy density for a 60°C temperature difference between charged and uncharged state is approximately 70kWhm^{-3}. The size of tank thermal energy storage systems depends on use; the store at Pimlico in London, supplying heat to 3256 homes, 50 businesses and three schools, used for short term balancing, is 2,500m^3 [2]. The solar thermal inter-seasonal storage system at Friedrichshafen in Germany [3] is 12,000m^3 with a storage capacity of approximately 0.84GWh, it supplies heat to 390 flats and a Kindergarten and in 2007 achieved an annual solar fraction of 33%.

Pit thermal energy stores are made by excavating a hole at a selected site and lining it with both plastic to provide water tightness and insulation to reduce heat loss. The pit is then either filled with water or a gravel-water mix. A well-insulated roof system is then installed to reduce heat loss. Charging and discharging of the store can either be by directly extracting hot water or indirectly via a heat exchanger. The energy density achievable for a water filled store is similar to a tank thermal energy store. A store with a gravel water mix will have a lower energy density.

If a suitable underground aquifer is available, an aquifer thermal energy storage system (ATES) may be developed. In this system, two bore holes are required which penetrate into the aquifer, heated water is injected in to one of the boreholes to charge the store and cold water extracted from the other. High temperatures of injection can cause changes in the geology of the aquifer and minerals may dissolve which can cause problems with fouling of heat exchangers. ATES systems can however, given suitable conditions, be cost-effective, storage volumes can be well over 10,000m^3. Due to the restriction in water temperatures that can be used for charging, energy storage densities are typically (at maximum) half those of tank storage systems.

If the geology is suitable, borehole thermal energy storage (BTES) systems can be developed. An array of vertical bore holes are drilled and plastic loop heat exchangers inserted followed by a thermally conducting grout, which enables the effective transfer of heat to and from the ground. Systems can be increased in size if required by adding additional bore holes. Such systems are often used in combination with heat pumps for building heating applications. The energy density achievable is generally about a quarter to a half that of the tank thermal energy storage system. The time constant for such stores is large with typically 3-5 years required prior to final operating conditions being achieved.

Borehole thermal energy storage systems and aquifer thermal energy storage systems will suffer from larger heat losses than the pit and tank thermal energy stores due to the lack of insulation. This can be alleviated in part by having large storage volumes. If significant unwanted water flow occurs near either a borehole or aquifer, store heat losses will be large.

Several reviews of underground thermal energy storage and seasonal storage have been presented with more detailed analysis of key aspects and specific detailed technologies [5-10]. An analysis of the specific storage costs of demonstration plants is presented in [4] that shows a very strong relationship between store size and cost. Small tank storage systems of 300m^3 of water costing about 470 Euro/m^3 compared to a cost of 120 Euro/m^3 for a 12,000 m^3 store. Aquifer, borehole and pit thermal stores are lower cost with an aquifer store with an equivalent storage capacity to 5,000 m^3 of water costing around 40 Euro/m^3 and a pit store with a volume of 75,000 m^3 of water equivalent costing around 30 Euro/m^3.

There are many examples of each of the above thermal storage system types reported in the literature. Examples of all system types can be found in the UK, however few details of these systems are presented in the peer reviewed journals.

Examples of large scale tank and underground sensible thermal energy storage systems using both solids and liquids are detailed in Table 1.

Table 1. Examples of Sensible Thermal Energy Storage Systems

Store Type	Example	Size/Volume	Comments
TTES	Pimlico [2]	2,500m^3	A system established in the 1950s to make use of heat from the then Battersea power station, currently used to provide a short term balancing function for a CHP system supplying 3256 homes, 50 businesses and three schools.
TTES	Munich [3]	5,700m^3	Seasonal thermal energy storage system serving 300 apartments, 2,900 m^2 area of solar collectors and a 1.4 MW absorption heat pump; started operating in 2006.
ATES	Rostock [11]	20,000m^3	Seasonal thermal energy storage systems serving 108 flats, 980m2 solar collectors, a 30m^3 water buffer store and a 110kW heat pump; started operating in 2000.
ATES	Klina [12]	Not detailed	To provide cooling and heating with two 195kWt heat pumps for a hospital complex of 400 beds + ancillary services, payback period estimated at 8.4 years. 1280 tonnes CO2 saved.
PTES	Eggenstein-Leopold-shafen [13]	4,500m^3	System installed with renovated buildings, 1,600m^2 of solar collectors with two 600kW gas boilers and a 30m^3 TTES.
PTES	Marstel [4]	75,000m^3	To date the largest pit thermal energy storage system. Linked with 33,365m^2 solar collectors, 1.5MW heat pump and a 4MW biomass boiler for the provision of heat to 1,500 members of the district heating scheme at Marstel.
BTES	Neckarsulm [11]	63,360m^3	Installed in 1997 supplies heat for 300 apartments, 5,760m^2 of solar collectors, 538 boreholes, a gas condensing boiler is included to supply additional heat if required.
BTES	Nuremberg [14]	Not detailed	Installed in 2008 to provide heat to a 3 floor office building with total area of 1530m^2 using a ground source heat pump. 18 boreholes of 85 m length used.

In addition to storing heat, large scale water stores have been used to store chilled water to help meet peak building cooling loads and to provide buffer storage for district cooling systems.

3.3.2 High Temperature Sensible Thermal Energy Storage

High temperature large scale thermal energy storage systems have been developed for use with concentrating solar thermal power systems to enable 24 hour generation of electricity using solar energy. The molten salt thermal energy store associated with Andasol 1 in Spain can be used to provide 7.5 hours electrical power generation at 50MWe from a molten salt store operating between temperatures of approximately 298-391$^{\circ\mathrm{C}}$ [15]. High temperature stores (>400$^{\circ\mathrm{C}}$), based on the concept of heat transfer tubes contained within a solid concrete element, have been developed and prototypes tested by Deutsches Zentrum für Luft- und Raumfahrt (DLR) [16].

A similar concept is proposed by New Energy Storage Technology (NEST) with storage systems of 1GWht designed [17].

An example of the use of packed bed stores, which illustrates their wide range of potential applications, is the low temperature gravel store system proposed by isentropic to work at -160˚C [18] with relatively short term storage duration.

3.3.3 Sensible Heat Storage Research Challenges

The IEA Energy Technology Systems Analysis Programme (ETSAP) and the International Renewable Energy Agency (IRENA) have recently produced a technology brief in the area of thermal energy storage [19]. In this document they give a breakdown of how technologies rate in terms of status with respect to Market readiness to R&D. The details for sensible heat storage are provided in Table 2. From this table it can be seen that there are still significant research challenges in sensible heat storage.

Table 2. State of Development, Barriers and Main R&D Topics for Different Sensible Heat Storage Technologies [19]

Technology	Status (%) Market/R&D	Barriers	Main R&D Topics
Hot water tanks (buffer stores)	95/5	-	Super Insulation
Large Seasonal Storage Water Tanks	25/75	System Integration	Materisla, tank construction, stratification
UTES	25/75	Regulation, High Cost, Low Capacity	System Intergration
High Temperature Solids	10/90	Cost, Low Capacity	High Temperature Materials
High Temperature Liquids	50/50	Cost, Temperature <400 °C	Materials

The main barriers to implementation are the current costs of the systems and the challenge posed by the requirement to integrate the different technologies and systems so that they work in an optimal energy efficient manner, for example different heat sources and different stores, (capacity and duration) on a single network.

Although sensible heat storage is widely used with many examples of systems being deployed successfully over a wide range of different temperature ranges with different storage capacities, research challenges still exist including:

- Development of new materials with improved thermal properties
- Systems integration
- Optimal sizing and modularity
- Optimal operation and control
- Improved charge and discharge characteristics
- Improved insulation
- Deep geothermal storage

3.4 Latent Heat Storage

In latent heat storage systems, materials undergo a change of phase generally from solid to liquid, with the energy storage material selected depending on the temperature of application. Due to the change of phase from solid to liquid, in most cases the phase change material (PCM) is different from the heat transfer fluid with either the PCM encapsulated in containers with the heat transfer fluid flowing over them or by using a heat exchanger inserted into a store full of PCM material. Significant benefits over sensible heat storage materials, in terms of the potential energy storage density and required volume for the store, can be realised if the temperature range of the application is close to the phase change temperature. However if a wider temperature range of operation is permitted then it is probable that a sensible heat storage approach will be more cost effective.

The energy stored in a phase change material when heated from below the phase transition temperature to above the phase transition temperature, assuming the phase change occurs at a set temperature, is:

$$Q = mC_{p1}(T_{pc} - T_1) + mh_{pc} + mC_{p2}(T_2 - T_{pc}) \qquad \text{(Equation 3)}$$

Where Q is the energy stored above the datum temperature T1
m is the mass of phase change material
Cp1 is the specific heat capacity of the phase change material when solid
Cp2 is the specific heat capacity of the phase change material when liquid
T1 is the datum temperature
T2 is the final temperature
Tpc is the phase change temperature
hpc is the enthalpy of phase change/heat of fusion

From this equation it can be seen that, in addition to high phase change enthalpy, high specific heat capacity is required if the operational temperature difference (T_2-T_1) is large.

Although to date there are not a great number of PCM based thermal energy storage systems deployed, there are many reviews of PCM materials and systems in the literature [20-24]. In the review of PCMs by [20], the main criteria for selecting a phase change material are specified to be:

- A phase transition temperature that matches the required operating temperatures
- High latent heat of fusion per unit mass/ volume
- High specific heat to provide additional sensible heat storage
- High thermal conductivity to enable effective charging and discharging
- Little volume change on phase change to reduce required space for expansion
- No or little sub-cooling during freezing
- Chemical stability with no degradation over multiple cycles and low/no reactivity with encapsulants
- Non-poisonous, non-flammable, non-explosive
- Abundant
- Low cost

A wide range of materials are available for use in latent heat energy storage systems, providing the potential for application at a range of different temperatures from freezing, to high temperature storage applications. The different materials proposed for use as phase change materials include aqueous salt solutions, water, gas hydrates, paraffins, fatty acids, salt hydrates and eutectic mixtures, sugar alcohols, nitrates, hydroxides, chlorides, carbonates and fluorides. The temperature range covered by these materials is from below -20°C to above 700°C. Specific details of different materials and properties can be found in the reviews [20-24], an illustrative sample of the materials to show the range of temperatures that are possible is presented in Table 3; for more complete listings [20-24] should be referred to.

Many of the phase change materials available unfortunately have low thermal conductivity. When transferring heat to the store, the material adjacent to the heat exchange surface melts and natural convection occurs increasing the rate of heat transfer above that achievable by conduction alone. When extracting heat from the store the liquid adjacent to the heat transfer surface when cooled below the phase transition temperature will solidify on the surface reducing the heat transfer rate by forming an insulating layer. This can lead to slow rates of heat discharge and a decrease in the temperature obtained from the store below that expected from the phase transition temperature. To reduce this effect and take advantage of the phase change phenomenon, it is important that there is effective heat transfer between the heat transfer fluid and the phase change material. Different approaches trialled have used various forms of encapsulation including thin plates and small spheres; introduction of heat conducting elements into the PCM has also proved a popular approach with for example metal fins and carbon fibres being used [20].

Table 3. Illustrative examples of Materials Proposed/Used as Phase Change Materials selected from [20-24]

Material	Melting Temperature (°C)	Heat of fusion (kJ/kg)	Density (kg/m^3)
H_20	0	333	998
RT5	7	156	860
RT27	28	179	870
RT54	55	179	900
$AlCl_3$ +NaCl (66-34)	93	201	-
KNO_3	333	366	2110
NaCl(56)-44$MgCl_2$	430	320	-

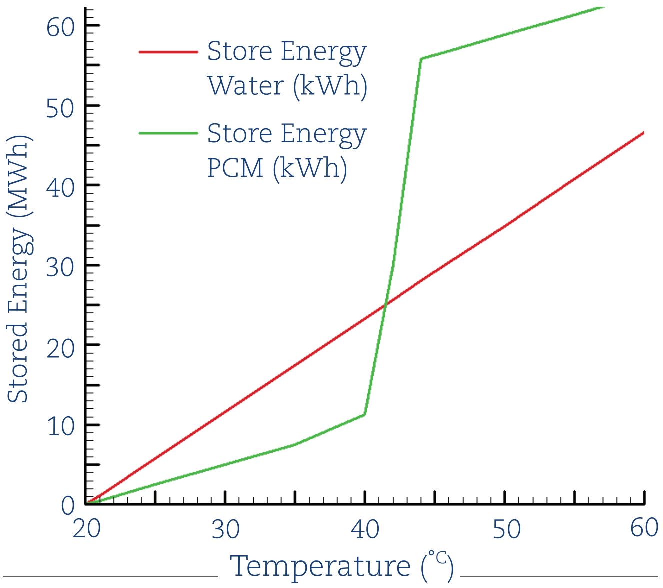
Figure 14 shows the calculated energy that would be stored in a 1m^3 volume water store based on an initial store temperature of 20$^{°C}$ compared to a 1m3 store using PCM RT44. 10% of the store is considered to be filled with water, (the heat transfer fluid) and 81% with PCM, the remaining 9% is left void to allow for PCM expansion.

It can be seen that if the store is operated within a temperature range from 30-50$^{°C}$, the energy stored in the PCM store is over 2.3 times that of the water store. If the operating temperature range can be reduced closer to the phase transition temperature and effective charging and discharging still realised, the advantage in terms of heat storage of the PCM store can be over 3 times that of the water store.

From the review articles it can be seen that many applications for phase change materials have been proposed, for example space heating, space cooling, greenhouse heating, waste heat recovery systems, clothing, ice slurries, building products, and although some have reached commercialisation, large scale market impact in the UK is yet to be achieved.

The use of the building fabric as sensible thermal energy storage is an important aspect influencing how the building responds to heating or cooling.

Figure 14. A comparison of the stored energy with temperature for a PCM and water based store of 1m^3 volume and a datum temperature of 20˚C



Thermal energy storage in the building fabric and thus temperature buffering may be reduced when retrofitting buildings with internal insulation to reduce heat loss. The internal insulation effectively makes the buildings lightweight, with more rapid response to heating or cooling. In periods of high solar gain overheating may be an issue. Microencapsulated phase change materials with phase change temperatures of 21-26$^{°C}$ have been included in plaster board to provide an element of tuneable thermal mass. For satisfactory operation over a daily cycle it is essential that the heat absorbed by the PCM during the day to limit peak room temperature is subsequently discharged, this requires the room temperature to be at a lower value than the phase transition temperature for the night period.

An example of high temperature latent heat storage development for process heat application is provided in [25], phase change energy storage systems with temperatures of application within the range 120-250$^{°C}$ are being developed to provide process steam for use in the manufacture of aerated concrete.

3.4.1 Latent Heat Storage Research Challenges

For low temperature applications of phase change materials linked to building cooling, products are available on the market. Further research to improve performance and reduce cost when integrated into buildings and building service systems is required. For high temperature applications significant research is required before commercial systems are available. Table 4 provides details of the main R&D topics identified in [19], this table does not consider the temperature range that would be beneficial for use with air source heat pumps. The major challenges in this temperature range are achieving an energy storage density significantly better than water (> 2.5 times) in the temperature range 35-55$^{°C}$ with stores scalable to meet several hours of space heat load with sufficient discharge heat output rate.

Table 4. State of Development, Barriers and Main R&D Topics for Different Latent Heat Storage Technologies [19]

Technology	Status (%) Market/R&D	Barriers	Main R&D Topics
Cold Storage(Ice)	90/10	-	Ice Production
Cold Storage (Other)	75/25	High Cost	Materials, Slurries
Passive Cooling Buildings	75/25	High Cost, Performance	Materials Encapsulation
High Temperature PCM (waste heat)	0/100	Cost, Low Capacity	Materials, PCM Container

Challenges exist in terms of achieving the theoretical performance in terms of charge/discharge rates for many PCM systems, research is required to enable system designs to be produced that achieve or come close to theoretical values.

3.5 Thermochemical Heat Storage

Thermochemical heat storage uses reversible chemical reactions to store large quantities of heat in small volumes. On applying heat to a material it breaks down into two components that are then stored separately, when the components are brought back together they recombine and release heat, this is illustrated schematically in Figure 15.

Of the heat storage technologies, thermochemical systems are the least developed requiring complex reactor designs to achieve the desired operational performance at scale. They do, however, offer significant benefits in terms of both energy density and the ability to store the reactants separately at room temperature for long periods of time with little or no degradation in stored energy content.

Figure 15. Schematic Diagram illustrating the Thermochemical Heat Storage Process

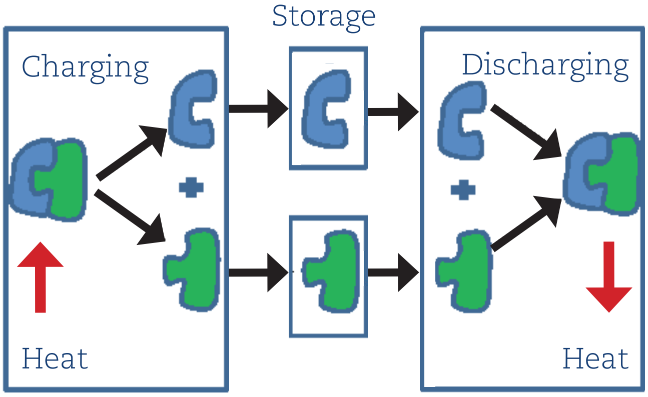


Table 5 presents details of some of the materials that have been proposed for thermochemical heat storage. If successful designs can be developed that perform to the predicted theoretical levels with no materials degradation on repeated cycling they could enable long term effective heat storage with compact storage systems to be realised. However, much research is required into materials and reactor design before this will be achieved. The higher energy density realisable with phase change materials led to the development of a system in Germany in which waste heat from an industrial process was stored in a large phase change module mounted on a lorry [40]. The lorry was then driven several miles and the heat discharged to a load. The much higher energy density that thermochemical heat storage offers could enable heat to be transferred efficiently in this way; [19] suggests that 3MWh of heat could be transported by truck and standard freight container.

A review of thermochemical energy storage systems is presented in [26] and initial experimental results and a possible design for a small scale thermochemical heat storage system for space heating applications presented in [27]. A selection of suggested thermochemical heat storage materials with approximate energy storage densities and charging reaction temperatures are provided in Table 5.

Table 5. Examples of Materials that have been identified in the literature to be interesting for Thermochemical Heat Storage [26]

Thermochemical material	Reactant A	Reactant B	Approximate Energy Storage Density of thermochemical material (kWh/m³)	Charging Reaction Temperature (°C)
$CaSO_4.2H_2O$	$CaSO_4$	H_2O	389	89
$MgSO_4.7H_2O$	$MgSO_4$	H_2O	778	122
$Fe(OH)_2$	FeO	H_2O	611	150
$FeCO_3$	FeO	CO_2	722	180
$Ca(OH)_2$	CaO	H_2O	528	479
$CaCO_3$	CaO	CO_2	916	837

3.5.1 Thermochemical Heat Storage Research Challenges

From Table 6 it is clear that thermochemical heat storage requires significant research and development for systems to reach the market.

3.6 Summary

The different thermal storage technologies (sensible, latent and thermochemical) are at different levels of development. To date, the only approach to be used on a large scale both in terms of number of installations and storage capacity to provide significant levels of energy storage is sensible heat storage. The use of latent heat energy storage is finding applications in the built environment with phase change materials used in building cooling systems to displace peak cooling loads and by using microencapsulated PCMs in the building fabric.

High temperature applications of phase change materials for process heat are being investigated for industrial processes in which heat demand is variable. The thermochemical heat storage technologies offer significantly higher energy storage capacities, however they are at the early stages of research and development.

The technology brief [19] quantifies the potential of using thermal energy storage in Europe. They estimate that in the building and industrial sectors by the more extensive use of thermal energy storage, 400 million tonnes of CO_2 emissions could be avoided. The major barriers to TES technologies are associated with cost and long term performance.

The greatest use of heat at present in the UK is for space heating, this is likely to remain the case unless the building stock is radically transformed. A low carbon approach using electricity even with heat pumps will result in significantly increased winter electrical loads. Effective distributed heat storage may have a significant role to play and help to reduce the number of generators with low capacity factor and utilisation and reduce the need for electrical network strengthening. Two case studies have been undertaken for domestic heating using data for a dwelling in Derby and the Pimlico district heating scheme.

Table 6. State of Development, Barriers and Main R&D Topics for Different Thermochemical Heat Storage Technologies [19]

Technology	Status (%) Market/R&D	Barriers	Main R&D Topics
Adsorption TES	5/95	High cost, complexity	Materials and Reactor Design
Absorbtion TES			
Other Chemical Reactions			

Case Study 1: Potential for Thermal Energy Storage in the UK Housing Stock

4

4.1 Introduction

Following on from the work described previously, the built environment in the UK is responsible for over 40% of national carbon emissions, with almost two thirds of this resulting from the UK's domestic housing stock. Within a typical UK domestic household, approximately 80% of the energy consumption is for space and water heating. In order to tackle this problem and help to meet national carbon reduction targets, the UK Government has launched the 'Green Deal' where energy efficiency refurbishments to the existing stock are financed via loans that are paid back through energy savings achieved. Amongst the technologies that are being offered through Green Deal, heat pumps are a key component, and it is expected that significant numbers of these will be deployed over the next few years. This will place demands on the electricity supply.

4.2 The Approach Adopted

This case study outlines analysis undertaken to assess the feasibility for thermal storage to be installed to support the operation of a heat pump in the UK domestic retrofit context, and its impact for energy supply utilities. Attention is paid to the sizing of the thermal store in relation to house thermal performance, heat demand and the availability of space, together with impacts for energy utilities under a specific demand side management strategy. Consideration is given to two types of storage media: water and phase change material (PCM).

The approach adopted involved a steady-state model for predicting heat loss rates, together with the degree day technique for estimating domestic heating energy consumption. Validation of this approach was undertaken through measurements in an occupied dwelling. The model was then used to forecast heating energy consumption over a heating season for a range of house thermal performances. The role of a heat pump and thermal storage was then evaluated, with findings being placed in context with the wider English housing stock.

4.3 Modelling

An occupied detached dwelling located in Derby, UK was used for investigating the concept of domestic demand side management strategies based on thermal energy storage with heat pumps. The house (Figure 16) has a usable floor area of 184.8m^2 spread over an upper and ground floor. It is bigger than a stereotypical UK detached house, and thus represents a challenging situation for the examination of the domestic heat storage approach. The house is occupied by a family of three persons.

The dwelling was built in the 1980s and was extended in the early 1990s, complying with the UK Building Regulations that prevailed at the time. At the same time that the house was extended, the cavity of the outer walls of the existing house was filled with polystyrene. Gas is used for space and water heating. Table 7 records the measured gas consumption of the house during winter, from October until April 2011.

Figure 16. Large Detached House in Derby, UK, used for the investigation

Table 7. Gas Consumption of the Detached House, recorded over Heating Season

Period	Actual Gas Consumption (KWh)	Actual Daily Gas Consumption (kWh/day)	Estimated Daily Gas Consumption (kWh/day)
18 Oct 2011-30 Nov 2011 (44 days)	3055	69.43	71.16
1 Dec 2011-21 Dec 2011 (21 days)	1925	91.67	97.87
22 Dec 2011-26 Feb 2012 (67 days)	6598	98.48	103.97
27 Feb 2012-18 Apr 2012 (51 days)	3896	76.39	78.57
Total Gas Consumption	15474	84.56	-

A one-dimensional steady state heat loss analysis was carried out for the property, employing data that included the dimensions and U-values of the house constructional components. A design heat loss rate was determined for an external air temperature of -2^{oC}, an internal air temperature of 18^{oC}. This resulted in a design heat loss rate of 9699.5 Watts, to be met by the installed gas boiler (of assumed COP = 0.7).

Using the design heat loss rate, the degree day technique was then employed to estimate the gas consumption of the house over a heating season. The comparison with measured values for actual gas consumption is also shown in Table 7, as daily gas consumption values (kWh per day). The good agreement observed between actual and estimated gas consumption suggests that the modelling approach adopted is sufficiently valid for use in assessing the performance of domestic heating systems comprised of a heat pump and thermal store.

4.4 Effects of Reduced Fabric Heat Loss

The thermal model was used to estimate the heating season (October – April) gas consumption of the detached house if constructed to comply with different UK Building Regulations (those of the 1980s, 1990s and 2010s). In effect, this shows the effect of improvements to the fabric on the seasonal gas consumption (Table 8).

Table 8 also presents the actual and estimated gas consumption figures for the current construction of the detached house, for comparison.

4.5 Heating with an Electric Heat Pump

Electric air source heat pumps (ASHP) are one of the key technologies to be offered under the UK Government's 'Green Deal' for the refurbishment of the existing housing stock. Electrically-powered, they align with the anticipated decarbonised all-electric future. However, as already discussed, mass migration to heat pumps might place unacceptable loads on the electricity supply grid. It is thus important to explore their use in conjunction with thermal storage and suitable demand management strategies in the domestic context.

Analysis was undertaken for the case of heating the detached house with an electric ASHP of assumed average COP = 2 (a conservative figure, that reflects findings from a recent evaluation programme by the Energy Saving Trust of heat pump installations in UK houses [28]). Heating is then supplied by electricity, not gas, for the house, with Table 9 showing the calculated electric energy consumption of the current construction and the electric energy consumption that would occur under different Building Regulations (1980s, 1990s and 2010s), for an assumed constant COP = 2.

Table 8. Effect of Fabric Improvements on Seasonal Gas Consumption, estimated using thermal model (actual and estimated consumption for current construction shown for comparison)

	Gas Consumption (kWh)				
Period	Actual Current Construction	Estimated Current Construction	Estimated based on 1980s Building Regs	Estimated based on 1990s Building Regs	Estimated based on 2010 Building Regs
Oct-Apr	15474	16159.3	27709.4	11232.7	6547.8

Table 9. Calculated Electrical Energy Consumption by Heat Pump for Construction meeting different Building Regulations

	Heat Pump Estimated Electrical Consumption (KWh)			
Period	**Estimated Current Construction**	**Estimated based on 1980s Building Regs**	**Estimated based on 1990s Building Regs**	**Estimated based on 2010 Building Regs**
Oct-Apr	5655.7	9698.4	3931.4	2291.4

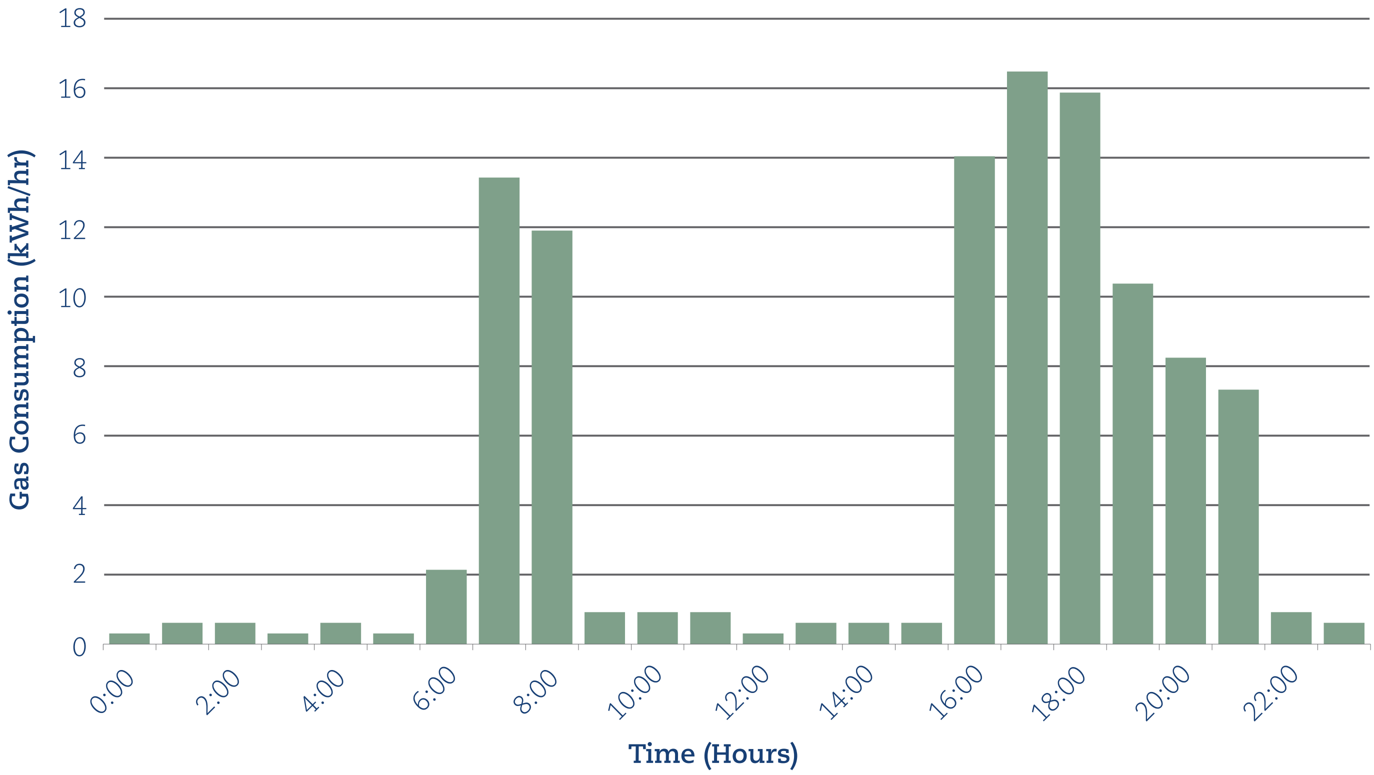
Table 10. Calculated Daily Heat Pump Electrical Energy Consumption for Current Construction and Construction based on the Building Regulations of the 80s, 90s and 2010s respectively

	Heat Pump Estimated Daily Electrical Consumption (KWh/Day)			
Period	**Estimated Current Construction**	**Estimated based on 1980s Building Regs**	**Estimated based on 1990s Building Regs**	**Estimated based on 2010 Building Regs**
Oct-Nov 2011	24.91	42.70	17.31	10.09
Dec 2011	34.25	58.74	23.81	13.88
Jan-Feb 2012	36.39	62.40	25.30	14.74
Mar-Apr 2012	27.50	47.16	19.12	11.14

For the sizing of short term thermal energy storage, the daily electric energy consumption is required rather than monthly or other periods. Using monthly data for gas consumption collected from the detached house in Derby for the period 18 October 2011- 18 April 2012 (183 days), and assuming electric heat pump COP=2, Table 10 presents the calculated daily electric energy consumption for different levels of fabric performances as required by different Building Regulations.

Table 10 shows that the maximum daily electric energy consumption occurs during the January – February period, these values were subsequently used for the sizing of thermal energy storage systems.

Figure 17. Typical Gas Consumption of Milton Keynes Energy Park Detached Dwellings



4.6 Hourly Heat Demand Profile

Records of hourly energy demand profiles for a range of house types (detached, semi-detached and terrace) in Milton Keynes, UK are available [29], with a typical hourly gas consumption profile being shown in Figure 17.

By assuming the hourly heat demand consumption profile of the detached house in this analysis to be identical to that recorded in the Milton Keynes houses, by proportion, figures for the hourly gas consumption of the detached house can be derived. Using the heat pump's COP they can be used to provide the heat pump electrical energy requirement and used in estimating the size of thermal store that would be required to enable peak demand to be shifted.

4.7 Thermal Energy Storage Analysis

Figure 18 illustrates the heat production profile and load shifting that is possible by including 36kWh of thermal storage. The aim of this is to shift heat generation and concomitant electrical load out of the periods when peak electrical loads occur with current use profiles. The heat pump in this instance is assumed to have an electrical input of 6kW with a COP of 2.

4.8 Estimated Sizes of Thermal Stores

The required storage volumes for the detached house, under different levels of fabric thermal performance (as required by the Building Regulations of the 1980s, 1990s and 2010s [30-32]), for a storage medium consisting of water and an operating storage temperature range of 20˚C to provide 3 hours of load shifting are detailed in Table 11. The analysis is then repeated for a storage medium assumed to be comprised of a phase change material with an effective heat storage density over the 20˚C temperature range equal to 3 times that of water.

From Table 11, it is evident that the required storage volumes for a PCM based store for new build and recently constructed dwellings can be accommodated in a reasonable space. For much of the existing stock however, significant retrofit to improve fabric performance will be essential. The final part of the analysis involved the wider consideration of this outcome by placing the detached house in context with the rest of the national housing stock.

Figure 18. Heat Pump Heat Generation for the Current Detached House Construction with Load Shifting used to minimise Electrical Loads between 6:00 and 9:00 and 16:00 and 19:00. The Thermal Store Capacity is 36kWh.

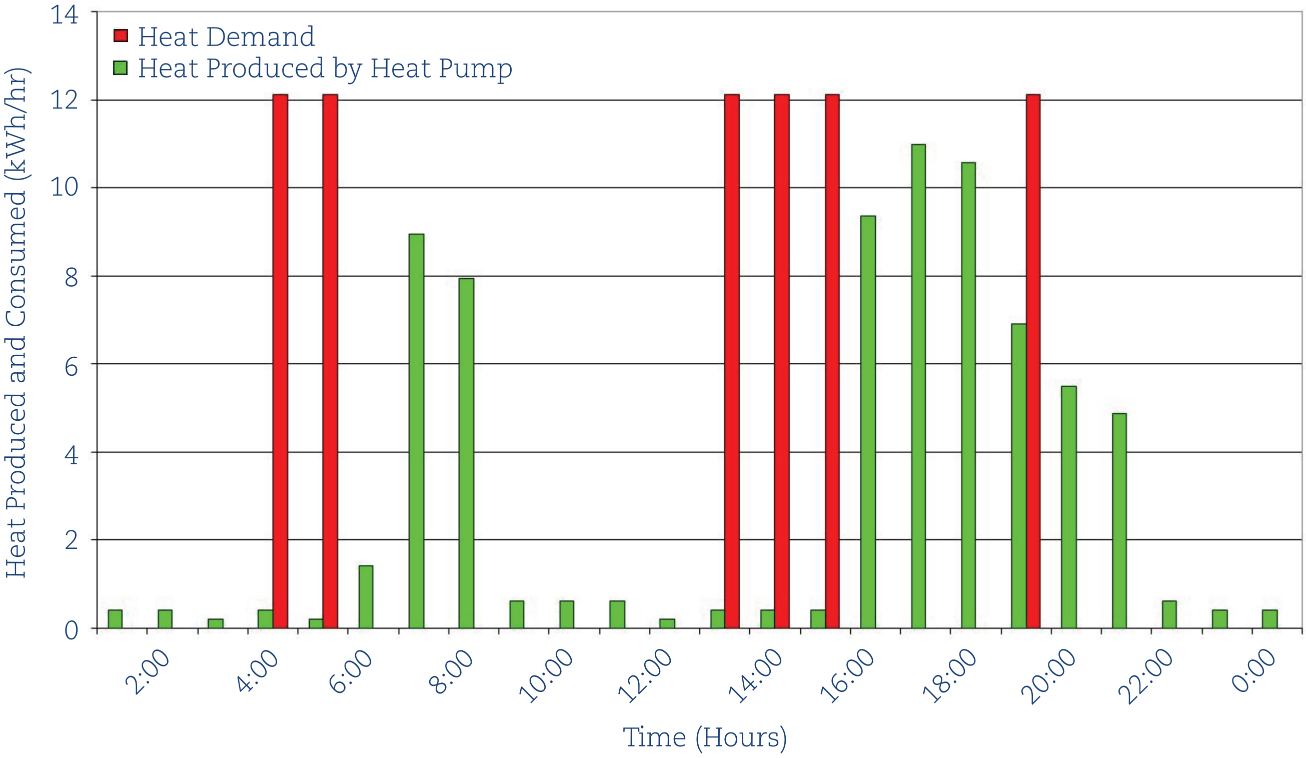


Table 11. Storage Volumes using Water and PCM as Storage Mediums for the Detached House with Fabric Complying with Building Regulations from different dates

Building Regs	Current Construction	1980s	1990s	2010s
Storage Volume (lt) Water	1543	2663	1097	560
Storage Volume (lt) PCM	514	898	366	187

4.9 Implications for Domestic Thermal Storage at the National Scale

In order to evaluate the potential on a national scale, the detached residence used in the analysis was placed in context against the English housing stock. Analysis of the English Housing Stock 2011 database [33] suggests that the following three archetypes of UK housing: detached, semi-detached, and mid-terrace, constitute about 17%, 26% and 18% of the entire English stock, respectively. Together, these total to approximately 60% of the English Housing Stock.

For each of these three archetypes, and using the data for the detached house in our case study as the example of the detached archetype, analysis was conducted to estimate the design heating load for all three types, based on typical dimensions, an assumed indoor air temperature of 18$^{°C}$, an assumed outdoor air temperature of -2$^{°C}$ (a typical UK design outdoor temperature – lower values would not represent typical conditions), and practical refurbishment following a Green Deal insulation improvement. Normalising against the detached case, the following ratios were determined (Table 13).

For the analysis presented in this report, the detached house used as the case study has a floor area of almost 185m^2 (ground and upper floor), which is larger than a typical UK detached house, and thus represents a challenging situation for the domestic thermal storage approach. Accordingly, semi-detached and terraced houses will be smaller than this, the ratios in Table 12 giving some indication. This suggests that a phase change store of volume significantly less than 187 litres would be sufficient to meet heat demands in many of the houses in the national stock following energy efficiency refurbishment to meet current standards, when used in conjunction with a heat pump of assumed COP = 2. Many houses, following the fitting of a condensing boiler and removal of a hot water tank, are likely to have the required space for installation of such a phase change store, since many hot water tanks had capacities in the region of 120 litres or more. However, this assumes that the space previously occupied by the hot water tank has not now been used for other purposes (airing cupboards or extending the usable space within a bathroom) which householders may be unwilling or unable to give up.

Table 12. Ratios of Design Heating Loads for English Housing types, normalised against a Detached House

House type	Design heating load (ratio)
Detached, insulated cavity and loft, untreated floor	1
Semi-detached with filled cavity, and loft insulated, untreated floor	0.47
Mid-terrace, untreated walls, but insulated loft, untreated floor	0.43

4.10 Case Study 1 Conclusions

Given that PCM storage is likely to become a viable technology in the next few years, it can be concluded that PCM-based thermal storage in conjunction with an electric air-source heat pump, offered as part of a Green Deal, could be technically possible in a retrofit context. If operated in conjunction with an appropriate demand side management strategy, this type of system has the potential to support domestic energy demand reduction whilst at the same time minimising supply challenges for the electricity utilities if at an appropriate cost. Many organic PCM materials are derived from the petrochemical industry although alternatives are becoming available. Cost data for small quantities of materials are not representative of larger quantities, PCM RT20 when purchased in quantities of more than 10 tonnes may be around £3.2/kg [40], assuming other PCMs are of similar cost, a store using 200kg of PCM would be around £650 more expensive than a water based store if additional heat exchanger costs are low.

Case Study 2: Exploring the Non-Technical Barriers to UK Deployment

5

5.1 Introduction

As outlined already within this report, thermal energy storage has the potential to store heat for later use over a period of hours, days, weeks or months. With a variety of approaches available, it offers the potential to supplement the energy supply system and is used in a wide number of applications in Europe and elsewhere and, as a means to optimise performance, is expected to become more widespread [34]. However there are a number of non-technical barriers to deployment in the UK and these are explored here, through use of a case study (Pimlico District Heating Undertaking, which includes a thermal energy store). There are a number of reviews of thermal energy storage systems, but few include details of the non-technical advantages and barriers to adoption. A review of social acceptance of a range of energy technologies [35] (although not including storage) recognises that this topic has had little attention to date.

5.2 The Approach Adopted

This case study was based on the limited published material about the Pimlico District Heating Undertaking (PDHU) and other relevant literature as well as a detailed interview with the key managers of the system, supported by a visit to the site. In addition to notes and photographs taken, the discussions were recorded and transcribed for later analysis. Other documents supplied by PDHU were studied to provide additional supporting material to the review. A detailed analysis of the thermal performance of the Pimlico District heating system falls outside the scope of this report but is included in an EngD thesis currently in preparation and available in summer 2014 [43] .

5.3 Pimlico District Heating Undertaking

Pimlico District Heating Undertaking (PDHU) is a district heating system that is owned and operated by Westminster City Council's CityWest Homes and provides heating and hot water to 3256 homes, 50 commercial properties and 3 schools in the Pimlico district of London, UK. Built in the 1950s, it originally used waste heat from Battersea Power Station. Now, with three 8MWth boilers and two 2MWth combined heat and power (CHP) engines, it generates electricity that is sold to the grid and provides heating and hot water to the properties served. The site is staffed by 2 full time engineers and 3 part time staff (manager, finance/contract manager, administrator). Additional contractors provide support for operational issues and minor repairs for the whole system and there is a call out system in place to provide out of hours service. The thermal energy store (see Figure 19), also referred to as the accumulator, is located above ground adjacent to the Energy Centre and Pump House, where the CHP engines are located and central operation takes place. The thermal store is a 41m tall tower, containing 2,500 tonnes water maintained at just below boiling point and contains approximately 18MWh of heat. The accumulator serves five purposes:

1. As an expansion tank to take up variations in water volume in the heating system
2. To act as a feed tank to make up losses in the system, although these can be minimal, e.g. 1.5 cubic meters over the whole system
3. To act as a heat store
4. To act as a seamless source of heat
5. To act as a cool store for the CHP engines

5.4 Social Impact

Thermal energy stores have the potential to provide positive social impact through the provision of heat. For those properties in fuel poverty (where the household cannot afford to keep adequately warm at reasonable cost),

Figure 19. The Thermal Store at Pimlico District Heating Undertaking

a district heating system, in conjunction with a thermal store, can provide a constant heat supply at a known cost. Within a district heating system where heat delivery is part of the social housing provision, it is possible to ensure that all homes are heated adequately and efficiently; this may need to be at a subsidised cost. The domestic properties at Pimlico make a payment for provision of heating and hot water at a rate based on the size of their property; the income of the household or length of daily occupancy is not considered. Comparison of price with conventional gas central heating is not easy – residents pay for heat, not fuel, and incur no maintenance costs of the system. A tenant in a one bedroom flat pays £479.77 per annum, those in a 5 bedroom flat pay £1,115.92 (2013 prices). Heating is provided to all properties from approximately 1 October to 1 June, and for up to 20 hours per day (5am to 1am in the coldest weeks, 6am to 11pm for the rest of the heating period), without metering. Commercial properties are metered and so pay for the exact amount of heat and hot water used. A boiler may be cheaper but it is likely that the home will be much colder as it would not be on for so many hours. The payment for heat, not fuel, also makes the district heating system more efficient for householders. The lack of an individual boiler within each property also maximises the living space.

Provision of heating for such an extended period of time ensures that vulnerable tenants who may need a warmer thermal environment to maintain health are well catered for. This increases the social impact, for example by reducing mould that may develop and so improving health. Provision of a thermally comfortable environment throughout a domestic property will enable the whole house to be used effectively, e.g. allowing comfortable space for children to do homework, people to bath in comfort etc. A thermal store can ensure there is always adequate warmth, providing a buffer during peak demand. The accumulator at Pimlico is used in this way, ensuring a constant service even during times of maintenance. There are occasional breaks in service, when there are more significant problems, such as major leaks, fire alarms etc. The length of this buffer depends on the level of charge of the accumulator, the external temperature, the season etc. In the summer, it may be possible to supply the whole community all day on the available thermal store; in the winter this may only last for an hour, but this could be enough to resolve more minor problems. At Pimlico, the CHP engines take 20-30 minutes to restart and regain full operational capacity, fast enough for the accumulator to provide a seamless supply to its customers. Financial rebates are offered if there is more than 24 hours interruption of service, but these are very rarely needed as the thermal store provides the buffer required.

This report has outlined how thermal energy as a by-product of industrial process can be stored and used later. The Pimlico system uses waste heat from its CHP engines which generate electricity. Previous research [36] found, through a questionnaire survey, that the source of the heat made a difference to its acceptability. Waste incineration as a heat source was considered positively by nearly half of survey respondents (n=323). Coal and gas power stations as heat sources elicited a more mixed response (positively by 39% and negatively by 24%); Nuclear power as a heat source received a more negative response (24% positive, 43% negative) and biomass energy as a heat source received a very substantial neutral/ don't know response, perhaps due to its relative unfamiliarity. Waste heat from industries was considered most favourably of all: positively by 67% and negatively by 10%.

The potential for a district heating system with a thermal store to bring a community together, through the sharing of a resource, was explored with the managers of the Pimlico system. However, there was a feeling that the heating system did not influence the sense of community. The provision of heating was seen as a part of their housing for which they paid individually.

5.5 Economic Impact

The introduction of a thermal store as part of a heating system offers a potential economic impact, through the requirements for initial installation and on-going maintenance. These will require new skills to be developed, including specialist knowledge, particularly in maintaining the system effectively and efficiently. The Pimlico system is carefully balanced to ensure that all properties receive adequate heat, despite their geographic dispersion. This means that any engineers working on the system need to have a good understanding of the impact of any changes they make, as these will be wide reaching. The Contracts Manager at PDHU has created a targeted induction pack which he provides to all contractors working on the system. Actions can affect the wider system without a contractor realising, and so this induction pack (and on the job support from the engineering team at PDHU), provides a site-specific guide to the whole system. This is critical to enable the provision of heat to all the properties and passes on the experience of the system to others. It was felt that there is a lack of skills within the UK in being able to work on this type of complex system and the transfer of accumulated knowledge from the senior engineer to the more junior at Pimlico shows evidence of a succession plan, but highlights the risk in the system through considerable knowledge being retained by only one or two people.

The PDHU accumulator is an open vented system and is emptied and checked every 10 years. In previous years, the tank was emptied, stripped, repainted and refilled, at considerable cost each time; a cost that is ultimately borne by the residents. Following a failed use of epoxy resin as the coating material (which was found to blister and cause corrosion where water had seeped through), the system now uses no coating on the inside of the tank, but relies on the corrosion control chemicals used to treat the water, which also protect the pipework. As a result, the maintenance is easier and cheaper. At the top of the tank, there is some corrosion at the air-water interface. This could be resolved with the introduction of a nitrogen cushion, but this would add to the operational costs and introduce health and safety complexities which were not seen as being cost-effective.

The accumulator at PDHU is insulated with cork, then covered with a plaster finish. Whilst there are thermal losses, the cost of upgrading the insulation was not felt to be worthwhile. A visual inspection shows wear and tear damage to this plaster, although this is generally superficial (see Figure 20).

Figure 20. Superficial damage to the Accumulator's Plaster Coating

The increase in numbers of thermal energy stores presents the opportunity for economic growth as part of their installation, operation and maintenance, although this may be balanced against a reduction in other heating systems. However, there is the opportunity for workers to retrain, developing skills and expertise in the new systems. The skills associated with the thermal stores are not likely to be significantly different to those required for the wider heating and power systems that the stores will service. However, these systems could require particular levels of expertise, particularly in understanding complex systems and the operation of large plant, as indicated by the staff at Pimlico. The system requires fine tuning to optimise its performance and this may require significant training and experience. If systems are run at sub-optimal levels, their benefits may be undone. With the limited number of thermal energy stores in the UK at present, expertise from elsewhere may be needed to initiate the market. However, once the technology is established, skills from within the UK will be developed effectively.

5.6 Behavioural Impact

A thermal energy store has the potential to buffer the provision of heat which could impact on behaviour in both positive and negative ways. The provision of a consistent supply of heat provides excellent service to a consumer, and could allow them to use their property more flexibly, if there activities do not need to fit with a regimented, routine supply of heat or power. This constant supply may, however, encourage people to use more energy, although this could reduce peak loads. Residents on the Pimlico housing estates have access to their heating and hot water for

17 hours a day (6am – 11pm) as the standard provision, which ensures their homes are warm all day and evening. The use of waste heat from other processes reduces the cost to the end user and the thermal store allows this heat to be used at a time when it is needed, rather than when it is supplied. Upham and Jones (2012) stress the need for district heating systems to ‘fit in’ with the existing routines and habits of users, if both systemic and contractual lock-in of a new system is to be achieved. A thermal store provides a flexibility to allow a range of behaviours that may not be possible with other systems without storage.

Properties served by the PDHU system, shown in Figure 21, are primarily multi-apartment blocks. As a result, they benefit from the heat transfer from neighbouring apartments. Whilst all properties are supplied with heating (and pay for this as part of their tenancy agreement), it would be possible to not heat a property and still keep warm from the surrounding building fabric. Other properties, particularly those with an exposed elevation have required additional heat and larger radiators have been installed. Secondary heaters (electric fan heaters) are used on occasion, but this practice is thought to be limited; there is no evidence of the use of air conditioning units to combat overheating. As a result, the provision of heating appears to meet the behavioural demands of the occupants. Heat loss is minimised from the external walls through cavity wall insulation and double glazing, although front elevations cannot be improved in this way as the estate is now a conservation area and so front doors and windows remain single glazed. Clearly, this is not an effective long term solution if carbon emission targets are to be met.

There are no domestic thermostats installed in the Pimlico properties as there is block control of the heating, with a weather compensated variable control system. Residents do have the ability to open windows if they are too warm and a visual inspection of the windows has been used in the past to identify if the control systems are working effectively. This simple, but somewhat imprecise, approach could be enhanced by more sophisticated sensor technology to ensure end user needs are being met at a minimum system cost.

5.7 Built Environment Impact

Thermal stores can be very large and, if above ground, can have a significant impact on the built environment. They may take space away from the community, or change the local landscape. If planned sensitively, a thermal store can have minimal impact, allowing landscaping to hide an installation, or for good design to make it a feature.

Figure 21. Properties served by the PDHU and its Thermal Store

Residents at Pimlico see the thermal store, a 41m tower very close to their properties (see Figure 22), as "an old friend" which they have accepted. It has architectural appeal and, together with six housing blocks, was Grade II listed in 1998. This shows the positive potential for design to enhance the introduction of thermal storage systems.

The design of underground thermal stores also needs to consider the impact on the built environment in relation to siting decisions. Whilst many can be covered with a layer of soil which can be replanted, they may restrict the inclusion of trees. At the Okotoks Borehole Thermal Energy Storage (BTES) Project in Canada [37], deep-rooted trees were permitted only in areas outside the borehole field, which affected the appearance of the surrounding environment.

5.8 Case Study 2 Conclusions

Information in this specific area in the literature is very limited and so evidence for this review has been drawn from expert knowledge and a case study of the Pimlico District Heating Undertaking in central London. Further work in this area is needed, including more extensive qualitative reviews of existing systems to fully understand the issues. However, this research, which provides a detailed quantitative analysis of the thermal energy store in use, was not available for this report and so does not form part of the review.

Thermal energy stores offer a number of non-technical advantages. The ability to balance a variable supply and demand ensures that all businesses and residents on the system can be provided efficiently with heat and hot water to meet their needs. A thermal store also offers an emergency buffer to ensure seamless supply in the event of planned or unexpected maintenance. This ensures that the most vulnerable members of the community are also provided with heat and hot water. This can improve living conditions, reducing damp and hence mould growth, and generally improve levels of thermal comfort. In a district heating system such as the Pimlico District Heating Undertaking, heating provision can be adjusted centrally to ensure these standards are maintained even in very cold winters at a fixed and known cost. However, this cost is inflexible and so residents are not able to adjust their expenditure according to their income, but the delivery of more efficient heating or supplementing those on lower incomes could provide an effective way of ensuring those in fuel poverty are provided with adequate heat and hot water throughout their property.

Figure 22. The Thermal Storage Tower has architectural appeal

There is a potential skills gap in managing and operating complex systems with thermal stores. Initially, these skills may need to be imported, but the UK has the capacity to develop appropriate skills quickly. The inclusion of thermal storage as part of the UK energy system provides an opportunity to develop new skills, but will inevitably reduce the attention on disaggregated heating systems. It is important that thermal storage systems are sympathetically introduced to the built environment, to ensure they are accepted by the local community. Good design can ensure that the impact on the local environment is positive.

The thermal store at Pimlico District Heating Undertaking produces better control; without the thermal store, the system would need to vary in operation to meet the changing demand, and so run inefficiently. As the lead engineer commented: "When you are dealing with literally millions of pounds worth of heat each year, those differences do matter".

Application areas for thermal energy storage in the UK

6

If electrification of heat is pursued on a large scale it will have a major impact on the winter peak electrical load. For example the installation of 2 million domestic air source heat pumps with a coefficient of performance (COP) of 2, each designed to provide 8kW of heat, will require additional generation capacity of 8GW. Diversity in heat demand does occur, however since the external ambient environment temperature is a major factor determining demand, on a cold winter day many systems will operate concurrently. The Committee on Climate Change recently published Fourth Carbon Budget review [41] estimates a range of between 2 and 6 million heat pump installations by 2030 with 4 million being the most probable. Bagdanavicius and Jenkins [42] consider the effects of installing Ground Source Heat Pumps in a residential area in Wales for synthesised building energy loads and hypothetically consider the additional electrical loads if half (13.15 million) of the UK dwellings had a ground source heat pump installed. Air source heat pumps although with lower COP are lower cost, easier to install and have a greater potential for application in the domestic sector and hence are considered here. Table 13 provides details of additional peak electrical loads that can be expected for different numbers of air source heat pumps for different domestic dwelling heat loads.

If the heat load follows a profile similar to that of current use the maximum loads will occur in the late afternoon/early evening between 16:00 and 19:00 and in the morning between 07:00 and 09:00. By providing three hours of heat storage it would be possible to shift the peak load so that it is not coincident with current electrical peak load. For comparison the current peak electrical load in winter is under 60GW. The required storage for the 3 different heat loads in Table 13 to enable a 3 hour shift in heat pump operation from the peak electrical load period is 12kWh, 24kWh and 36kWh for suitably-insulated properties. For water based heat storage with an operating temperature range from $55^{\circ C}$ to $35^{\circ C}$ the volumes required are approximately 0.5, 1 and 1.5 m^3, clearly large compared to currently installed domestic hot water storage systems. If a phase change material based store can be developed that provides effective charge and discharge powers with an energy density of 2 to 3 times that of water, the required store volumes are more reasonable being a half to a third that of a water based heat store. For an energy density of 2.5 times that of a water based storage system the volumes for 12 and 24kWh of storage become 0.2 and 0.4m^3 respectively. There will be an additional cost compared to water based stores, this will however be partly mitigated by reduced materials required for the store, reduced construction requirements due to lower weight and reduced space required. Other financial gains are related to a reduction in peak generation capacity required and network strengthening which may be deferred.

The heat stored and the equivalent electrical storage that this represents is presented in Table 14. It is clear from Table 14 that the equivalent electrical energy storage that can be realised with large numbers of relatively small heat stores is large compared to current energy storage capacity in the UK.

Table 13. Additional Electrical Load for different numbers of Installed Air Source Heat Pumps for different Peak Heat Loads and different COP

	Electrical Load GW given								
	Heat Load 4kW			Heat Load 8kW			Heat Load 12kW		
Air Source Heat Pumps Installed ('000)	**COP = 1.5**	**COP = 2**	**COP = 3**	**COP = 1.5**	**COP = 2**	**COP = 3**	**COP = 1.5**	**COP = 2**	**COP = 3**
500	1.333	1	0.666	2.666	2	1.333	4	3	2
1000	2.666	2	1.333	5.333	4	2.666	8	6	4
2000	5.333	4	2.666	10.666	8	5.333	16	12	8
4000	10.666	8	5.333	21.333	16	10.666	32	24	16
6000	16	12	8	32	24	16	48	36	24

Table 14. Equivalent Electrical Storage for different numbers of installed Air Source Heat Pumps for different Peak Heat Loads and different COPs with 3 hours of Heat Storage

	Equivalent Electricial Storage GW given								
	Heat Load 4kW			Heat Load 8kW			Heat Load 12kW		
	12kWh Heat Storage			24kWh Heat Storage			36kWh Heat Storage		
Air Source Heat Pumps Installed ('000)	COP = 1.5	COP = 2	COP = 3	COP = 1.5	COP = 2	COP = 3	COP = 1.5	COP = 2	COP = 3
500	4	3	2	8	6	4	12	9	6
1000	8	6	4	16	12	8	24	18	12
2000	16	12	8	32	24	16	48	36	24
4000	32	24	16	64	48	32	96	72	48
6000	48	36	24	96	72	48	144	108	72

6.1 District Heating

The opportunities for installation of district heating in the UK could be considerable when compared to other European countries that have significantly more heat networks. There are however a number of key issues that need to be considered:

- The availability of a waste or unutilised heat source
- The heat load in the area to be served by the heat network
- The seasonal variation of heat load
- The willingness of all/most of the potential customers to utilise the heat network
- The cost of installation
- The price at which heat can be sold

Taking each point in turn:

- Industrial waste heat, if at the correct temperature, or heat from existing electrical power generation or CHP plant, can be provided to a heat network at low cost, however the heat generation and heat demand should both be in the local area to keep pumping costs and heat losses low
- If the area to be served by the network does not have a high heat requirement per unit area, the installed heat mains will be longer than for a high heat requirement area, this will increase pumping costs and pipe work heat losses. More energy efficient buildings have lower heat loads, making new build developments and areas that have had deep retrofit less appropriate for district heating
- A large heat load that requires heat all year round, an anchor load, will reduce seasonal variation in heat demands resulting from space heating and will aid in efficient financially viable operation
- If installing an heat network into an existing development each dwelling will already have its own heat supply system, (boiler), unless the costs of heat are sufficiently low, not all occupants will switch to the heat network supply, consequently the heat requirement that the network will see will be reduced making it less viable
- Installation costs and inconvenience associated with excavations to install large heat mains in busy urban areas are significant, particularly if the areas are heavily serviced
- A key parameter in determining the adoption of heat networks will relate to the price that heat can be sold for, the payback period of the network must be suitable so that investors obtain a reasonable dividend while heat is priced at a level that is more attractive to potential users than other available options

If the UK electrical supply is effectively decarbonised by 2030 then conventional CHP systems will no longer be the low carbon option. An alternative would be to use large scale ground or water source heat pumps if location permits. Rather than sizing heat pumps for peak heat loads and having sub optimal operation for the majority of the time, it will be appropriate to use thermal energy storage for in-day management; based on current systems a water based storage system could be used.

Using heat pumps rather than CHP engines means that the operation of the system is no longer going to be managed for electricity production and thus storage volumes may be sized to provide a shift in peak electrical load of, for example, 3 hours. Table 15 provides indicative water store volumes based on different numbers of consumers on a heat network for different average peak heat loads assuming that load shifting of 3 hours is required.

Assuming that the average number of consumers on a district heating systems is 1000, Table 16 provides details of the equivalent electrical energy storage for 3 hours of storage for different numbers of district heating networks.

6.2 Inter-seasonal Heat Storage

For inter-seasonal heat storage to become attractive due to the low number of charge/discharge cycles and quantities of heat required, it is essential that it is very low cost. To achieve low costs, systems need to be large. A consequence of this is that inter-seasonal heat storage using current technological approaches is only appropriate for use in larger heat delivery systems.

It may be attractive for district heating systems to use heat pumps in the summer period to charge underground storage to enhance winter heat pump COP if local geology permits. The possibility to use excess wind generated electricity in summer for such purposes may be attractive. If effective low cost thermochemical heat storage systems can be realised due to the high energy density and low self-discharge rates, inter-seasonal storage may become viable for other applications.

6.3 Industrial Heat Storage and Power Generation Options

For industrial processes that have time varying heat demands, are batch processes or produce waste heat, heat storage can be used to reduce peak loads, shift heat availability in time and allow waste heat to be better utilised. The development of compact thermal energy storage systems using high temperature phase change materials or thermochemical heat storage may prove attractive for industrial use. The potential high energy density of thermochemical heat storage may make it feasible for heat to be transported effectively from nuclear or CCS enabled heat producers.

Table 15. Storage Capacity and Volume required for different District Heating System sizes assuming Peak Load Shift of 3 hours

Number of consumers	Average peak heat load per consumer 4kW		Average peak heat load per consumer 8kW	
	Storage Capacity (MWh)	Store Volume (m3 ΔT=20°C)	Storage Capacity (MWh)	Store Volume (m3 ΔT=20°C)
500	6	257	12	515
1000	12	515	24	1030
2000	24	1030	48	2060
4000	48	2060	96	4120

Table 16. Equivalent Electrical Storage Capacity for different numbers of District Heating Networks with Load Shift of 3 hours assuming Average Network of 1000 consumers and Heat Pump COP of 3

Number of networks	Average peak heat load per consumer 4kW		Average peak heat load per consumer 8kW	
	Storage Capacity Heat (MWh)	Equivalent Storage Capacity Electric (MWh)	Storage Capacity Heat (MWh)	Equivalent Storage Capacity Electric (MWh)
100	1200	400	2400	800
200	2400	800	4800	1600
300	3600	1200	7200	2400
400	4800	1600	9600	3200
500	6000	2000	12000	4000

The idea of using nuclear power reactors for heat is not new [38]; indeed the Calder Hall nuclear power plant provided heat in addition to electricity in 1956.

Heat storage is also being explored for power generation options either using technology similar to that of isentropic [18], cryogenic storage or high temperature heat storage. The high temperature heat storage approach is particularly attractive when used with thermal plant since heat is stored prior to conversion to electricity allowing high efficiencies to be realised.

Conclusions

7

This report has presented the findings of an 18-month UKERC research project on the potential role that could be played by thermal energy storage within the UK energy system, within the context of aiming to achieve the UK's target of an 80% reduction in greenhouse gas emissions by 2050. Main areas of heat use have been characterised, thermal storage technologies have been reviewed, and assessments of technical feasibility, as well as the factors that could influence adoption, have been made.

Key conclusions are summarised as follows:

- Almost half of the UK's final energy consumption is for heating purposes, with space and water heating accounting for 63% and 14% of this, respectively. The domestic sector is responsible for 57% of heat use, mostly used for space heating. Large seasonal variations in space heating requirements mean that the annual heat load profile is not constant, with peak winter heat load being several times the average heat load.
- In terms of thermal storage technologies, sensible heat storage is currently the dominant approach, with store volumes ranging in size from domestic hot water tanks and electric storage heaters, to systems with volumes up to 70,000m^3 for inter-seasonal storage. The four main types of large scale low temperature-based stores successfully developed are tank, pit, borehole and aquifer-based thermal energy stores. Latent heat and thermochemical heat storage approaches can potentially provide greater energy storage per unit volume, but are currently at lower technology readiness levels.
- Large inter-seasonal stores are only sized for a maximum of a few hundred buildings for reasons of cost and financial return. A strong relationship exists between store size and cost, ranging from about £390/m^3 for small tank-based systems (volume around 300m^3), to about £25/m^3 for large pit-based systems (volume around 75,000m^3).
- In terms of the UK building stock, unless the stock undergoes radical transformation to greatly improve its thermal efficiency (refurbishment and replacement-based), then space heating will remain the greatest user of heat. Achievement of national emission reduction targets will therefore require low emission heating approaches. One of the key approaches comprises electric heat pumps operating with a decarbonised electricity supply. Another key approach is district heating. The feasibility of each of these has been assessed using two case studies.
- Case Study One focussed on domestic space heating, and determined daily winter heat requirements and daily peak heat requirements for a large family house in Derby, UK, assumed to be equipped with a heat pump and thermal storage technologies, and with house heating loads commensurate with compliance to the Building Regulations of 1980, 1990 and 2010. Thermal stores were sized to meet the maximum space heat load for a three-hour period to allow heat pump operation at periods of low electrical grid load. Required storage volumes were found to range from 2.6m^3 to 0.56m^3 for water based sensible storage, whilst a 'theoretical' phase-change material (PCM)-based store could reduce these volumes by two thirds. PCM storage is expected to become viable within the next few years, and its use in conjunction with an electric air-source heat pump could be technically possible in a domestic retrofit context. Operated with an appropriate demand side management strategy, such a system could potentially reduce domestic energy demand whilst minimising supply challenges for electric utilities.
- Case Study Two focussed on an existing district heating scheme in Pimlico, London, which includes a 2500m^3 thermal store. The thermal store was able to match supply and demand, as well as offering a buffering function in the event of maintenance, thereby providing benefits to the community as well as better control and aiding efficient operation. The introduction of thermal storage systems into the built environment should be done sympathetically, to ensure acceptance by the local community. Good design can help this.
- Provision of heat in the transition to a low carbon economy is a significant challenge. Heat networks currently supply less than 2% of the UK's space heating compared to approximately 16% in Germany. Heat networks allow large scale storage systems to be used that provide efficient storage and effective load shifting capability. Expansion of heat networks in the UK is possible in areas of high heat demand, although cost of installations are high at present. If the electricity supply is decarbonised, combined heat and power will no longer be the lowest carbon option and large MW-scale heat pumps may prove preferential.

- The wide-scale adoption of air source heat pumps for space heating will require significant investments due to the seasonal variation and magnitude of peak winter loads. Strengthening of the low voltage electrical network and significant additional generation capacity will be needed, in addition to significant building refurbishment, to reduce heat loads. Distributed thermal energy storage can provide a significant load shifting capability on a diurnal basis. This can, by reducing the peak load, lead to improved capacity factors for electrical generators by effectively flattening the daily demand profile. This could enable the construction of several GW of additional power generation capacity, that would be required to meet the peak winter heat load (with low capacity factors) to be avoided. However, without the development of effective latent or thermochemical heat storage systems, the storage volumes required will be large and difficult to integrate into existing domestic dwellings.

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