

Thermal energy storage in Scotland

Dr Jonathan Radcliffe, Dr Yongliang Li
University of Birmingham
July 2015



BIRMINGHAM
ENERGY
INSTITUTE

**UNIVERSITY OF
BIRMINGHAM**

Contents

Executive Summary.....	3
1 The potential role of Thermal Energy Storage in Scotland's energy system	6
1.1 Introduction	6
1.2 The case for thermal energy storage	7
1.3 Scotland's energy system.....	8
1.4 Energy system scenarios for Scotland	12
1.5 Overview of the role for TES	15
Section 1 References.....	16
2 Technologies and applications	18
2.1 Materials	18
2.2 Technologies and applications.....	22
2.3 Summary	30
Section 2 References.....	31
3 Implementation.....	34
3.1 Technology innovation in Scotland.....	34
3.2 Deployment case studies	37
3.3 Costs.....	40
3.4 Barriers to deployment	41
Section 3 References.....	44
4 Conclusions	45
 <i>Technical Appendices</i>	
Appendix 1 - Properties of sensible heat storage materials	49
Appendix 2 - Organic substances with potential use as PCMs	50
Appendix 3 - Inorganic substances with potential use as PCMs.....	51
Appendix 4 - Metals with potential use as PCMs	54
Appendix 5 - Alloys with potential use as PCMs	55
Appendix 6 - Current large scale (>100kW) cold storage projects	56

Executive Summary

Scotland's energy system is undergoing radical transformation to meet emissions-reduction targets, with impacts on all parts of the system: the supply of electricity will become increasingly variable from wind power; and patterns of use on the demand side will shift as heat is decarbonised from a mixture of biomass, district heat networks and electrification. Such changes can be managed, but it is important to recognise and prepare for the challenges, taking a long-term view consistent with climate change policy.

In the period to 2030, electricity and heat will become more interlinked, and so the energy system must be considered as a whole, not as isolated components. This is exemplified by thermal energy storage (TES), which could be a means of balancing supply and demand across electricity and heat. Deployment of TES technology in its many forms could avoid some of the costs of other options that will be needed to provide greater energy system flexibility, such as building new transmission lines to the rest of the UK or continental Europe, running gas power plant inefficiently, or relying on consumer response measures.

In general terms, TES can be the 'warehouse' between production and consumption of energy, with technologies that enable:

- electrical energy which is generated by renewables at times when demand is low, to be provided as heat or electricity at peak times;

or

- excess thermal energy from industrial processes or power stations to be stored and converted into useful heat or electricity when needed.

As described in the report, and summarised below in Table 1 and Table 2, TES covers a diverse set of technologies with a wide range of applications, some of which are ready to provide the required flexibility if they can be harnessed through effective controls, and deployed in a suitable market environment. However, many technologies, which could lead to step-change in performance and cost of TES, are at an early stage of development or are yet to be fully commercialised, and so need additional support.

There is a risk that short-term fixes to the energy system are put in place, because they are available and currently have the lowest cost, when other options could be better long-term solutions, though requiring some initial investment.

From consideration of Scotland's energy system and its future trajectory under current policies with an assessment of TES technologies, and mindful of the fact that heat policy is devolved to Scottish Ministers, we have identified the strongest potential opportunities for TES in Table 1. Though detailed modelling is required to quantify the level of benefit that could ultimately be achieved, we also identify some priority activities that may be undertaken (either by the Scottish Government, or at the UK and EU level with support from Scotland) to improve understanding of the technology and its applications:

- Development of thermal energy storage materials that can provide more effective domestic heating from:
 - Electricity: many households in fuel poverty use inadequate storage heaters under Economy 7 tariffs. Improved technology would benefit the energy system and occupants.

- Heat networks: evaluation of schemes has shown the potential for lowering fuel-bills. Thermal storage could keep capital costs down by reducing the peak capacity required.
- Retaining the existing thermal energy storage, in the form of hot water tanks through regulatory or market-based approaches. Once removed from properties and replaced by combi-boilers, the space of a hot water tank is difficult to reclaim.
- Enabling 'smart' control technologies that allow distributed TES to respond to system signals. The roll-out of smart meters should allow excess energy from wind power to be stored instantaneously, and trials in Scotland have shown this to be technically feasible.
- Testing of seasonal thermal storage, to meet winter heating demand from heat stored in the summer. For winter heat demand to be wholly met by electricity would require a massive investment in fossil-fuel generation capacity, which could be partly offset if seasonal storage was viable.
- Supporting demonstration of near-to-market TES technologies at scale, thereby bringing innovative companies to Scotland. A number of technologies are approaching commercialisation, but require scale-up to de-risk further investment. We also need to understand better how the energy system responds to new technologies.
- Building capacity and capability in TES in Scotland to take advantage of an emerging market. With such a high renewables penetration, Scotland will be well-placed to take advantage of the development of TES and other flexibility options.
- Assessing policy and regulatory frameworks for energy storage, to avoid the creation of unintended barriers to deployment. TES, and energy storage in general, is not currently recognised as providing a valuable service to the energy system, and the business case for commercialisation struggles in the current policy environment and market framework.

Thermal energy storage in Scotland

Energy system challenge	Application for TES	Time/energy scale	TES technology area	Development stage and TES principle (see Table 2)
Meeting high demand for thermal energy in winter from electrified heating, avoiding low capacity factors from generation	Capturing excess thermal or electrical energy in the summer, discharging as heat in winter	Months GWh	Large-scale ground-based heat stores	Demonstrated: sensible heat stores, e.g. above ground reservoirs, underground aquifers, subsurface rock
Providing efficient community-level heat and power whilst meeting variable thermal/electrical energy demand profiles	Balancing co-generation of electricity and heat.	Hours – days 10s MWh	Heat stores alongside CHP	Deployed: hot water accumulators
Meeting daily peak demand for thermal energy from electrified heating, avoiding low capacity factors from electricity generation and networks.	Storing off-peak electrical energy, discharging as heat at peak times	Hours 10s kWh	Domestic-scale TES devices	Deployed: sensible heat, hot water cylinders In Development: phase-change materials In Research: thermochemical materials
		Hours kWh+	Building fabric	Deployed: sensible heat - thermal mass of building Demonstrated: building integrated phase-change materials
Increased energy demand for cooling, for data centres and buildings	Reduction in demand from grid at peak times, and reduction in daily cooling peak of buildings	Hours 10s MWh	Cooling/chilling	Deployed: sensible heat and phase change - water/ice chiller air con systems
Integrating variable renewable energy production (in particular wind/solar)	Balancing supply and demand over weather-related timescales	Hours – days 10s –100s MWh	Solar thermal	In early deployment: sensible heat underground aquifer for small community In early deployment: phase-change materials with solar thermal power generation
			Cryogenic energy storage	Demonstrated: phase change liquid air 300kW pilot plant operational, 5MW liquid nitrogen plant in construction
			Pumped thermal energy storage	In development: 1.5MW/6MWh demonstrator planned

Table 1 Thermal energy storage applications.

TES principle	Materials	Technology	Advantages	Disadvantages
Sensible heat	Water, gravel, pebble, soil ...	Water-based (water tank, aquifer), rock or ground-based	Environmental, cost, simplicity, reliability	Low energy density, heat losses, site construction capex
Latent heat / phase change	Organics, inorganics ...	Packaged in passive storage systems	Higher energy density, constant temperature	Lack of stability, corrosion, high cost of storage materials
Thermochemical reactions	Metal chlorides / hydrides / oxides...	Adsorption/absorption, chemical reaction, at high temperatures	Highest energy density, low loss for long duration storage	Poor heat transfer, cyclability, high cost of storage material

Table 2 The physical principles which allow the storage of thermal energy.

This report was commissioned by ClimateXChange to provide Scottish policy makers with a review of thermal energy storage technologies and their potential application in Scotland.

1 The potential role of Thermal Energy Storage in Scotland's energy system

1.1 Introduction

Across society we store items so that they can be used when needed, rather than when they are produced. For most goods, this storage is taken for granted when they can be kept in warehouses of some sort. For conventional fossil (and nuclear) fuels, these exist as piles of coal, gasometers, underground gas storage reservoirs, and so on. When electricity or heat is generated, the energy must be utilized or it will go to waste. Electricity in particular must be used instantaneously; heat will gradually disperse into the environment.

Traditionally, electricity usage profiles have been well-understood so that power stations could be run to meet the demand. To provide heat, gas-based hydrocarbons (recently natural gas in the UK) could be physically stored (including in the pipe network) and combusted for space heating when needed, or used in power stations as a fuel for electricity generation.

Storage of thermal energy itself has played a role in the UK's energy system for some decades, with Economy 7 tariffs (and variants) which incentivised off-peak electricity use coupled with electrically powered storage heaters; and hot water tanks alongside gas central heating. Economy 7, and storage heaters were introduced to meet a supply-side challenge, with nuclear base-load generating electricity when demand was low. Hot water tanks were a response to the demand-side, to provide large quantities of hot water when needed (in France, hot water tanks with electrical immersion coils were used to balance the country's much larger nuclear fleet).

The energy trilemma, which describes the challenges from balancing the issues of energy security, cost and environmental impact, forces us to reconsider previous models of supply and demand in the energy system. Electricity from renewable wind and solar cannot be generated at will, and is variable by its nature; whilst its uses are expanding into transport and heating. Decarbonisation of heat may also be achieved through heat networks, and other low carbon fuels. Designing more flexible and 'smart' energy systems will be critical, with studies showing that energy storage can allow such systems to be operated more efficiently.[1]

The role of thermal energy storage in a UK context has been described by Eames et al[2] and by international organisations[3], but Scotland's ambitious emissions-reduction and renewable energy targets, as well as the different heat geographies of Scotland, make an assessment of its options urgent and important. This report describes:

- how Scotland's energy system is changing,
- what role thermal energy storage could play in Scotland,
- the range of thermal energy storage technologies that are being developed,
- thermal energy storage innovation in Scotland,
- potential applications for thermal energy storage in Scotland, and
- discussion of deployment pathways.

1.2 The case for thermal energy storage

Heat policy is devolved to Scottish Ministers. Heat plays a central role in Scotland's energy system, with non-electrical heat demand accounting for 55% of all final energy demand in 2011[4]. Including electrical heat and electrical cooling demand increases this figure further. At the same time, heat is routinely 'wasted' as a by-product of power generation and industrial processes.

Scenarios to meet the emission targets (described in section 1.4 below) show the need to decarbonise heat through both demand and supply sides. The Scottish Government illustrates this in its 'Heat Hierarchy': reducing demand, improving efficiency and using low carbon/renewable sources (Figure 1).

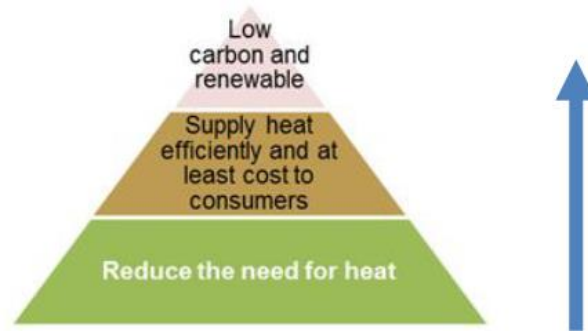


Figure 1 The Heat Hierarchy

The extensive use of decarbonised electricity to power heat pumps, and through heat networks would have deep implications; potentially requiring network infrastructure to be reinforced to meet peak demand, with thermal power generation back-up on standby in the event of low output from wind or solar. The annual running times (or utilisation factors) of thermal plant would diminish, leading to a challenging market environment, as they still need to recoup the investment but from lower output.

Given how important heat is to society, and plans to reduce emissions associated with its use, having a robust and coherent strategy for thermal energy is critical if policy goals are to be met. As part of this, thermal energy storage (TES) technologies can have a positive impact, allowing both supply and demand side measures, in electricity and heat, to be effectively deployed. To assess the potential of TES requires analysis of both the system, and the technologies which could fit into that system. Such detailed systems analysis has been lacking, though a recent study has shown how TES in cooling applications can bring wider energy system benefits, rather than simply reducing end-user costs.^[5]

In general terms, TES can be the 'warehouse' between production and consumption of energy, with technologies that enable:

- electrical energy which is generated by renewables at times when demand is low, to be provided as heat or electricity at peak times;

or

- excess thermal energy from industrial processes or power stations to be stored and converted into useful heat or electricity when needed.

This gives four use-cases:

1. electricity stored thermally for heat;
2. electricity stored thermally for electricity;
3. thermal energy stored thermally for heat;
4. thermal energy stored thermally for electricity;

with the time in storage potentially varying between minutes and months.

Many TES technologies can work across these use cases, therefore when considering how thermal energy storage could be applied in Scotland, a 'whole-systems' approach must be taken.

1.3 Scotland's energy system

Key points that emerge from considering Scotland's current energy system, relevant to this study, are:

- Peak demand for gas in the winter is 2.5 times that of electricity, in energy terms; and winter peak gas demand is 4 times that of the summer demand for gas.
- A large proportion of households are off the gas grid, but households in Scotland prefer installing biomass over heat pumps to provide renewable heat, compared to the rest of the UK.
- Average use of domestic and non-domestic gas in Scotland is higher than the rest of the UK, but both gas and electricity consumption are declining more rapidly than the rest of the UK.
- Almost a quarter of domestic electricity usage is by households with Economy 7 meters, with storage heaters. Space heating from electricity is often inadequate, though most are not situated in homes with 'good' energy efficiency rating.
- A majority of customers with electric heating are in fuel poverty.
- A small proportion of heat demand is served by district heating schemes.
- Hot water tanks (domestic thermal stores) are being replaced by combi-boilers providing instantaneous hot water.

These factors, described in the sub-sections below, point to the opportunity for, and threat to, a wide take-up of new thermal storage technologies in Scotland.

1.3.1 Headline statistics

Scotland consumes 10% of the UK's total energy consumption (12.5 mtoe - the equivalent of 12.5 megatonnes of oil)[6] with 8.3% of the population (or 8.5% of the population of Great Britain, for which many of the comparisons will be made against). Petroleum products comprise a greater proportion of fuels, compared to GB, with industry a larger relative consumer and transport a lower consuming sector (

Figure 2).

Electricity consumption in Scotland is 25.9 GWh (8.9% of GB) from 2.98 million (10.0% of GB) meters, therefore the average 8,685 kWh/yr is somewhat lower than for GB, (9,690 kWh/yr). There has been a 12% reduction in consumption since 2005 in line with rest of GB.[7]

Scotland has the highest mean domestic gas consumption of 14,300kWh (GB 13,700kWh) per meter, with 1.97m meters (out of 23m across GB), and has seen a 3.5% decrease since 2012 - the largest drop across GB. Since 2005 there has been a reduction of 5,700 kWh, again above GB average of 5,400 kWh.

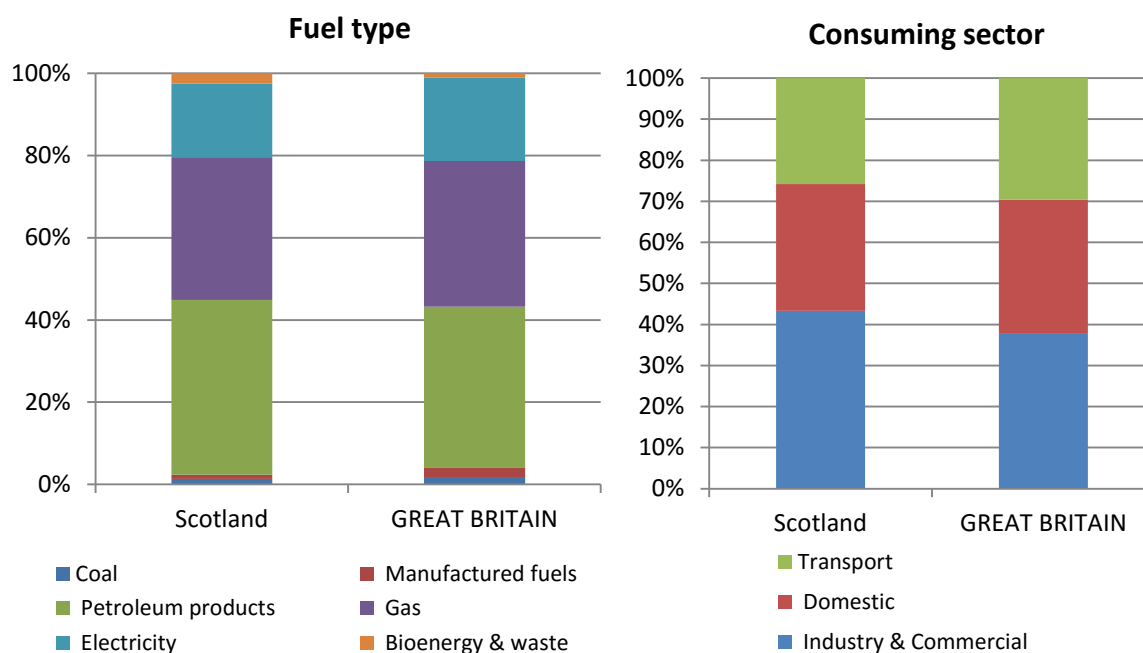


Figure 2 Energy fuel and consumption in Scotland compared to Great Britain as a whole. (Source: DECC)

1.3.2 Electricity

Electricity consumption in Scotland is split 41% domestic : 59% non-domestic (compared to GB which has a ratio of 37:63). Within the domestic sector, figures for Scotland are close to those of GB: the average consumption is 3,900kWh; and 17% of meters are on Economy 7 with average 5,300kWh. Economy 7 meters account for 23% of domestic electricity consumption. Consumption across Scotland is shown in Figure 3.

Scotland saw the biggest annual drop in consumption in GB in 2013 of 2.9%, and GB's second largest drop since 2005 – a reduction of 780kWh.

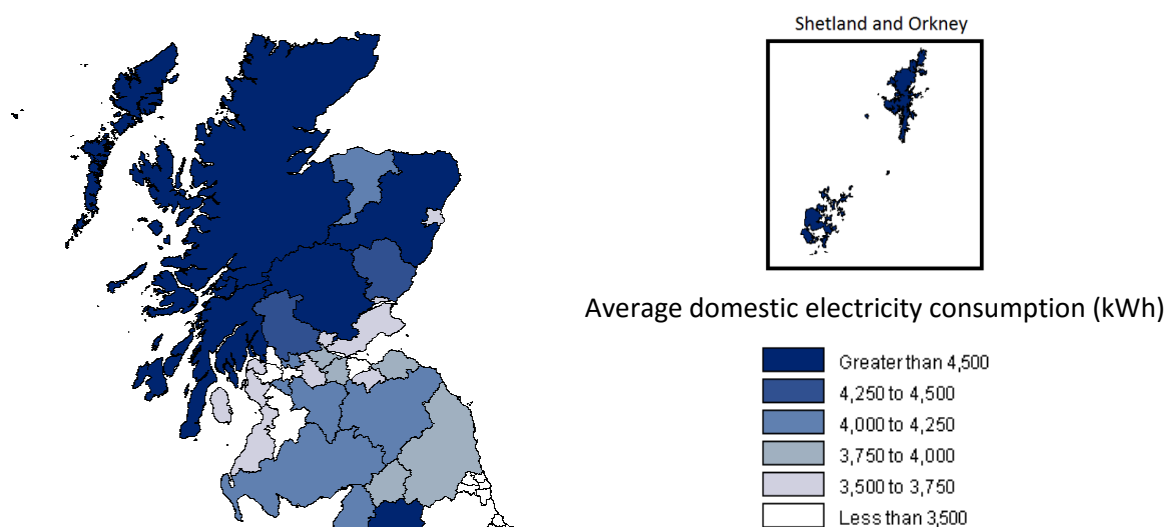


Figure 3 Domestic electricity consumption in Scotland. (Source: DECC)

1.3.3 Gas

Scotland has the highest mean domestic gas consumption of UK regions of 14,300kWh per meter (4.4% above GB mean), though consumption has been declining faster than the GB average (Figure 4). 17% (408,000) of Scottish households are estimated to be off-gas-grid, compared with 10% for GB[8].

Non-domestic average consumption was 848,000 kWh per meter (through 24,000 meters) in 2013, the second highest in GB (GB average was 670,300 kWh).

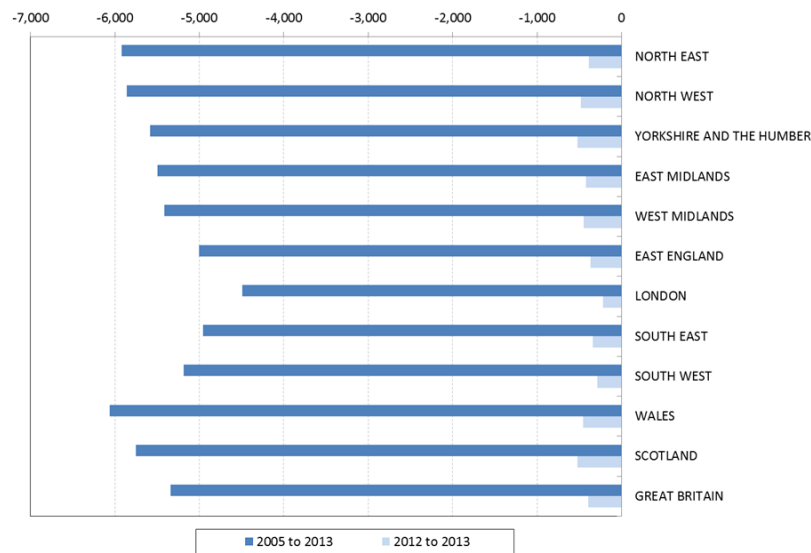


Figure 4 Change in mean domestic gas consumption. (Source: DECC)

1.3.4 Heat

1.3.4.1 Fuels

In 2009, just over 60% of all energy consumed in the UK domestic sector was used for space heating and a further 18% used for water heating. Overwhelmingly the most common heating fuel overall is mains gas: 78% of Scottish households (around 1.9 million) use mains gas for heating, 13% use electricity and 6% use oil.

Flats have a higher use of electricity for heating, and for post 1982 flats, 30% use electricity for heating. The share of the market for combination (or 'combi') boilers is now approaching two-thirds of all boilers in the UK with condensing combi boilers making up a third of all installed gas and oil boilers.

25% of householders in Scotland report that their heating only sometimes or never keeps them warm in winter, 42% of these used electricity as the main fuel (compared with 23% gas, 22% other).[9]

Daily gas and electrical demand for Scotland across winter 2013/14 is shown in Figure 5. What is noticeable is how the winter peak in gas demand is four-times that of the summer, and the demand can increase or decrease by 50% in less than a week. By contrast, electricity demand varies much less, the winter peak is twice the summer minimum, and the variability within the year is more predictable – with regular drops seen at weekends.

Also, there is a sizeable difference in the amount of energy being delivered in winter, with gas providing 2.5 times that of electricity (at the peak gas delivers 200GWh a day, compared to 80GWh a day from electricity).

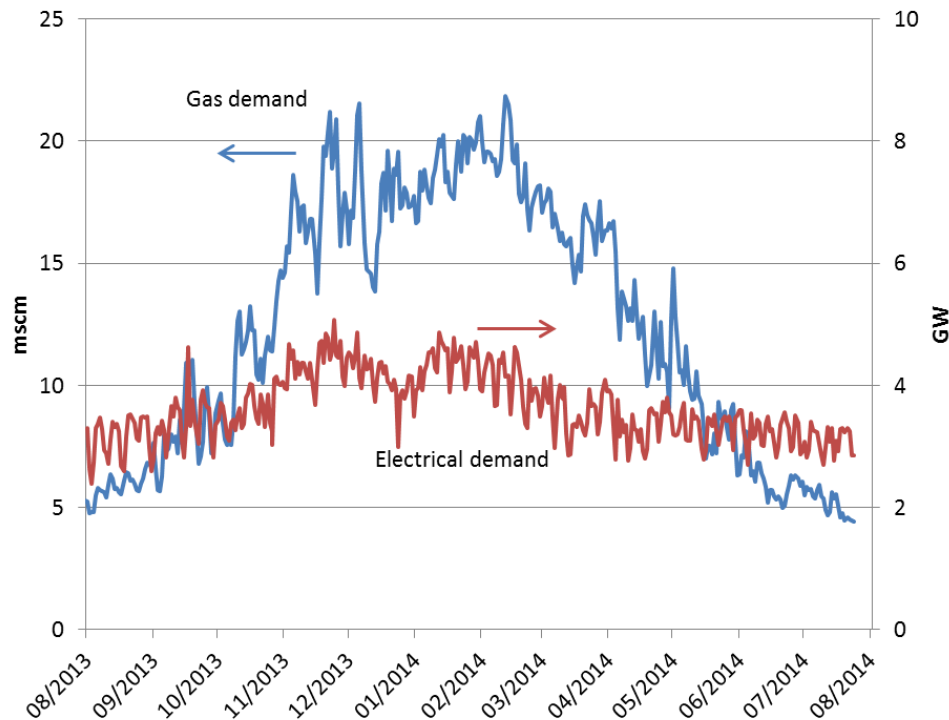


Figure 5 Daily demand figures for distribution-level gas (blue line, left-hand axis), and peak electricity for Scotland (red line, right-hand axis)[10]. (Source:National Grid)

1.3.4.2 Heat networks and heat sources

Scotland has 65 heat networks (3.7% of the number in GB), of which 45 are classified as small and 15 medium/large.[11] District heat networks (DHNs) connect 10,000 homes, with 0.2TWh heat provided to domestic and non-domestic users.[12] The Heat Network Partnership for Scotland, as a collaboration of agencies, has mapped these schemes, available at <http://www.districtheatingscotland.com/>. A number of case studies, ranging from domestic connections in tower blocks, to low rise flats and public buildings, are described with assessments of technical and economic characteristics. This includes one example with a thermal store comprising 3 x 10,000 litre water tanks[13].

The Scottish Government commissioned development of a 'heat map' to provide heat demand and sources (<http://heatmap.scotland.gov.uk/>). Whilst most energy generation sources are given, the 'waste' heat from industrial processes is not included – ten such sources have been compiled for this report from DECC data based on EU ETS information, amounting to over 6TWh/year (Table 3).

A report by AEA investigated the opportunity for using 'waste' heat from power stations in district heat networks, finding them not to be financially viable under existing conditions, although it is technically possible.[14] Studies of the Aberdeen heat network also found that technical and economic feasibility were insufficient to drive take-up of district heating.[15]

Whilst the long-term viability of heat networks will be dependent on technology costs, market conditions and non-economic barriers, the Scottish and UK Governments are supporting their deployment. Financing by the Scottish Government has provided £7m loans for 33 heat network projects since 2011. Evaluation by the Energy Saving Trust has found that fuel bill savings for customers have been between 22.5% (when switching from electric) to over 40% (when switching from oil)[16]. A further £8m in loans has been made available in the period 2014 – 16.

Site Name	Heat Flow (TWh)	Sector	Site Name	Heat Flow (TWh)	Sector
Grangemouth Olefins	1.22	Chemicals	Tullis Russell Papermakers	1.13	Paper and Pulp
Fife Ethylene Plant	0.98	Chemicals	Lafarge Cement UK PLC site 3	0.10	Cement
DSM Dalry	0.27	Chemicals	O-I Alloa Plant	0.11	Glass
Shell UK Ltd Fife NGL Plant	0.24	Chemicals	Grangemouth Refining	1.56	Oil Refining
The Girvan Distillery	0.13	Food and Drinks	Grangemouth CHP LTD	0.43	Oil Refining

Table 3 Non-power industrial heat sources in Scotland. (Source: DECC)

1.3.4.3 Renewable heat

Domestic RHI deployment statistics show the take up of Air-Source or Ground-Source Heat Pumps (ASHP/GSHP) in Scotland is below that of GB, being equal to that of biomass, and accounting for 42% of installations. In England, 54% of installations are for ASHP/GSHP, 24% for biomass and 15% for solar thermal.[17]

1.3.4.4 Thermal storage

In 2010, 12% (279,000) of dwellings in Scotland used storage heating as their primary form of heating (84% boilers, 2% room heaters, 1% community heating). Of these dwellings 84% had new style storage heaters (also known as slimline), 8% had old style (usually pre 1978) and 5% had fan assisted. Typically, less than half of energy supplied to storage heaters overnight is available by the evening.[18] However, only 30% of households which use electricity have a good 'National Home Energy Rating' (NHER).[19]

Half of households do not have hot water (HW) storage. In UK surveys, many respondents said they disliked hot water tanks due to the space taken up and the inflexibility of having to plan when to heat water.[20] Of homeowners without a hot water tank, similar numbers said it would be difficult to find space, as those who said it would be quite easy to find space to install one.[21]

1.3.5 Fuel poverty

DECC statistics find that 27% of Scotland's population is defined as being in fuel poverty (compared to 14% in England and 29% in Wales).[22]

Scottish Government statistics have 39% of the population in fuel poverty [19] although there are differences in modelling and assumptions. In the same analysis, 56% of households with electric heating are reported as being in fuel poverty, compared to 35% of households with gas.

1.4 Energy system scenarios for Scotland

Whilst this paper focuses on thermal energy storage, as noted above, the use of electricity to provide heat is significant, and will increase to meet overall decarbonisation targets. Hence the production of electricity is examined here.

Scenarios for the Scottish Government show the dominance of variable renewables to meet policy aims (Figure 6).[23] Scenarios from WWF Scotland go further, by describing energy system pathways to 2030 for Scotland, which exclude coal and gas power stations by 2030.[24]

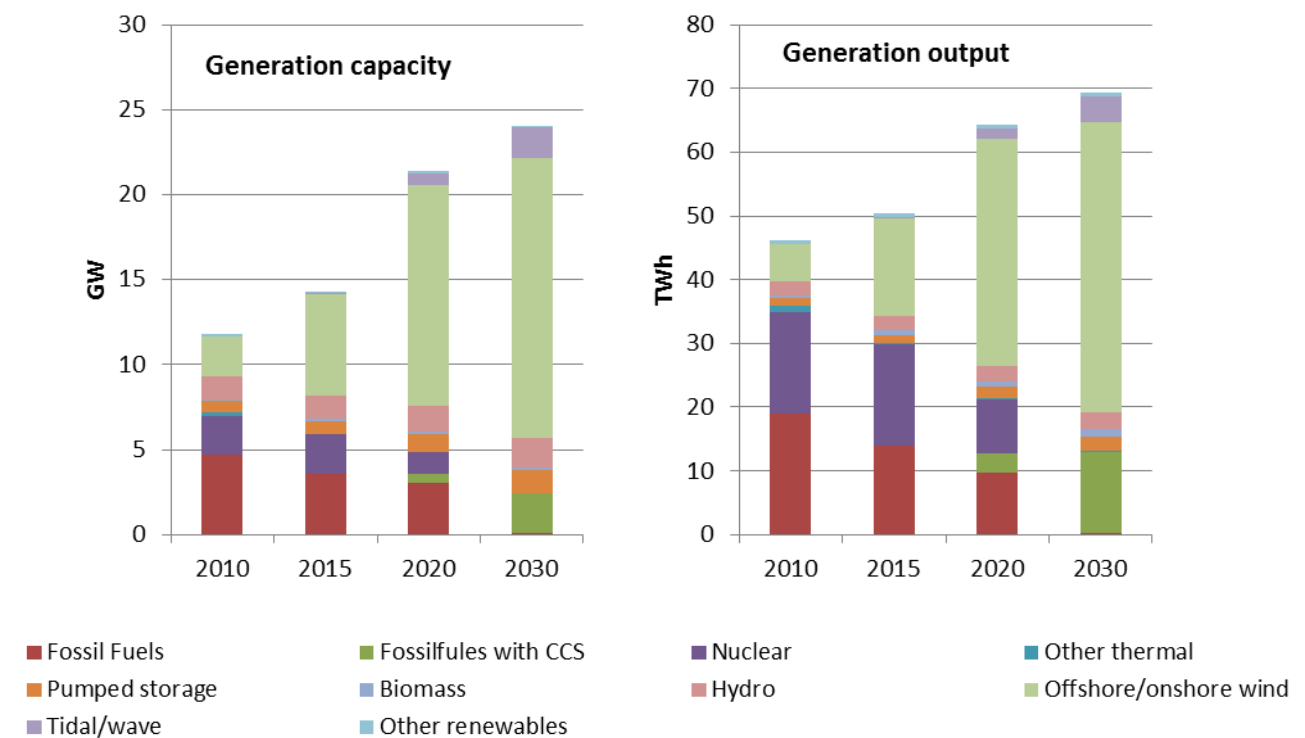


Figure 6 Electricity generation scenarios for Scotland (Source: Scottish Government, Electricity Generation Policy Statement, 2013)

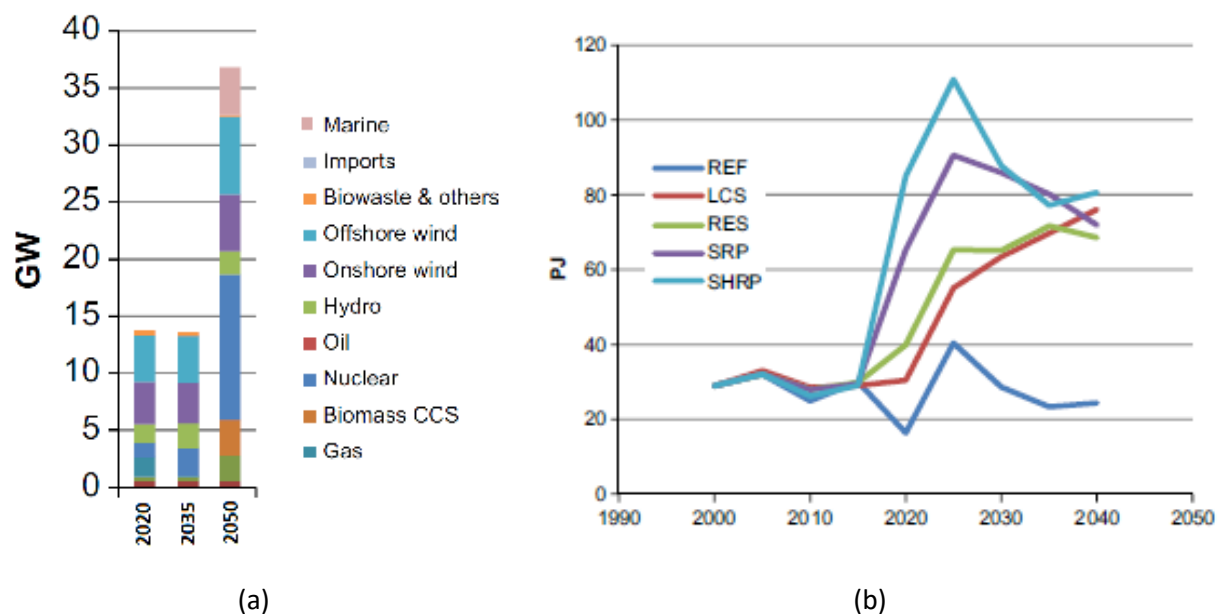


Figure 7 MARKAL model output for (a) generation capacity in Scotland and (b) net annual electricity flow to the rest of the UK (scenario SHRP is consistent with Scottish Government renewables targets, but does include nuclear) [26.] 1PJ of energy = 0.28TWh; 30PJ = 8.3TWh; 100PJ = 28TWh¹

¹ It was not possible within the scope of this project to calculate the net annual flow to the rest of the UK in GWh.

Analysis using TIMES/MARKAL (a technology-rich bottom-up cost optimization modelling framework[25]) is being commissioned by the Scottish Government. Previous academic work has shown that meeting Scottish greenhouse gas emission targets would be achieved under scenarios consistent with UK targets, but additional deployment of renewables would be required to meet this target in Scotland.[26] Figure 7(a) shows the large increase in capacity to 2050 as heat pumps and electric vehicles are deployed; (b) shows the increasing net electricity flow to the rest of the UK from 2020 under this scenario.

In its 2014 report, the Committee on Climate Change found that Scotland had made good progress towards its targets in general.[27] However, an area of concern was renewable heat, where the pipeline of projects was found to be unlikely to meet either the 1.5TWh or 11% targets.

The need for more flexible energy systems as variable generation increases has been described by the Energy Research Partnership[28] [29] with the key challenges given in Table 4.

Timescale	Challenge
Seconds	Renewable generation introduces harmonics and affects power supply quality.
Minutes	Rapid ramping to respond to changing supply from wind generation.
Hours	Daily peak for electricity is greater to meet demand for heat.
Hours - days	Variability of wind generation needs back-up supply or demand response.
Months	Increased use of electricity for heat leads to strong seasonal demand profile.

Table 4 Energy system challenges from the large-scale deployment of variable renewables. (Source: Energy Research Partnership)

Such flexibility can be provided from four sources:

- Grid infrastructure: increasing connections within and between electricity systems, to allow import or export of power.
- Controllable ('dispatchable') generation: typically gas-fired power stations increasing or decreasing output.
- Demand side response: consumers decreasing their consumption. Often distributed thermal energy storage is seen as providing demand-side response, because the heating demand can be paused without noticeable effect for short periods.
- Energy storage.

Generation from natural gas-fired power plants has been the main source of flexibility in the UK. Interconnection to continental Europe has been low (though this is increasing), pumped hydro storage has been limited by suitable sites, and asking consumers to turn down their use has not been popular (though 'interruptible contracts' do allow for this in principle).

Box: Emission-reduction and energy targets for Scotland

The Scottish Government has set its own targets relating to greenhouse gas emissions and energy which go beyond those of the UK. Scotland's 2050 target of an 80% greenhouse gas emission reduction is complemented by a 42% reduction by 2020, compared to a 1990 baseline.[30]

For the energy sector, policy targets are to:

- meet at least 30% overall energy demand from renewables by 2020;
- reduce total final energy demand in Scotland by 12% by 2020, covering all fuels and sectors;
- source 11% of heat demand and 10% of transport fuels from renewables by 2020;
- deliver the equivalent of at least 100% of gross electricity consumption from renewables by 2020 with an interim target of the equivalent of 50% of gross electricity consumption from renewables by 2015;
- enable local and community ownership of at least 500 MW of renewable energy by 2020;
- demonstrate carbon capture and storage (CCS) at commercial scale in Scotland by 2020 with full retrofit across conventional power stations thereafter by 2025-30; and
- seek transmission system upgrades and increased interconnection capable of supporting the projected growth in renewable capacity.

In its Heat Policy Statement, the Scottish Government has set targets for district heat networks: for 40,000 homes to be connected, with 1.5TWh being delivered across the economy by 2020.[31]

1.5 Overview of the role for TES

Looking ahead over the coming 5 – 10 years, renewable electricity generated in Scotland will increase substantially to meet policy aims and will dominate the energy supply landscape. Balancing supply and demand over timescales of minutes through to months could require a trebling in connectivity to England (as shown in Figure 7b) or interconnection to mainland Europe, assuming back-up capacity from these systems is sufficient to cover a shortfall, and demand is enough to soak up excess, net of back-up/demand located in Scotland itself.

On the demand side, decarbonising heat is a critical component of achieving emission targets. Under the current market environment, some district heat networks may struggle to be financially viable (section 1.3.4.2 [15 and 2], but there are examples where loan financing has led to reductions in fuel bills for customers [16]. At the same time there is significant untapped resource in the form of 'waste' heat from power production and industrial processes.

There would therefore appear to be a strong case for using the increase in low carbon electrical supply and growth of heat networks to meet Scotland's heat demand. In both cases, TES has the potential to act as a key enabling technology in their deployment.

The strong seasonal profile of heat demand also presents challenges – if the UK's current gas heat demand was to be replaced by instantaneous electrical power, an extra 40 GW of capacity would be required[32], running with low utilisation.

For heat networks, the economic and carbon benefits are often complex, but the addition of TES in cost-benefit analyses may show value by reducing the capex needed to install plant to meet peak capacity.

² Department of Energy and Climate Change (2013) The Future of Heating

Given the above analysis of Scotland's current and future energy system, we can identify potential applications:

- electricity stored thermally for heat, over periods of minutes to months (e.g. heat pumps, storing heat in water or novel materials, underground TES);
- electricity stored thermally for electricity, over period of minutes to hours, to balance the network (e.g. pumped heat energy storage);
- thermal energy stored thermally for heat (e.g. capturing industrial waste heat for local space/water heating);
- thermal energy stored thermally for electricity, over period of hours (e.g. waste heat stored for later generation during wind lulls, with cryogenic energy storage)

The following section considers the various TES technologies which could meet such applications.

Section 0 References

- [1] Strbac et al (2012) Strategic Assessment of the Role and Value of Energy Storage Systems in the UK Low Carbon Energy Future <http://www.carbontrust.com/resources/reports/technology/energy-storage-systems-strategic-assessment-role-and-value>
- [2] Eames et al (2014) The Future Role of Thermal Energy Storage in the UK Energy System <http://www.ukerc.ac.uk/publications/the-future-role-of-thermal-energy-storage-in-the-uk-energy-system.html>
- [3] IEA Energy Conservation through Energy Storage (ECES) Programme, Task 42 Compact Thermal Energy Storage, see <http://task42.iea-shc.org/>
- [4] Energy in Scotland 2014, Scottish Government <http://www.scotland.gov.uk/Topics/Statistics/Browse/Business/Energy/Compendium2014>
- [5] Palacio SN, Valentine KF, Wong M, Zhang KM, Reducing power system costs with thermal energy storage, Applied Energy 129 (2014) 228–237; <http://dx.doi.org/10.1016/j.apenergy.2014.04.089>
- [6] DECC (2014) 'Sub-national total final energy consumption statistics: factsheet' <https://www.gov.uk/government/statistics/sub-national-total-final-energy-consumption-statistics-2010-factsheet>
- [7] DECC (2014) 'Sub-national electricity and gas consumption summary report 2013' <https://www.gov.uk/government/statistics/sub-national-electricity-and-gas-consumption-summary-report-2013>
- [8] DECC (2014) Sub-national electricity and gas consumption statistics <https://www.gov.uk/government/statistics/sub-national-electricity-and-gas-consumption-summary-report-2013>
- [9] Scottish Government (2014) Scottish House Conditions Survey - Key Findings 2013 <http://www.scotland.gov.uk/Publications/2014/12/6903/downloads>
- [10] Gas data come from the Scotland Local Distribution Zone, from which small-scale and domestic users are supplied (rather than large consumers, such as power stations). Electricity data are across all demand.
- [11] DECC (2013) 'Summary evidence on District Heating Networks in the UK' <https://www.gov.uk/government/publications/summary-evidence-on-district-heating-networks-in-the-uk>
- [12] Scottish Government (2014) Draft Heat Generation Policy Statement <http://www.scotland.gov.uk/Publications/2014/03/2778>
- [13] Carbon Trust (2012) Biomass Boiler Installation at Plockton High School, Plockton http://www.districtheatingscotland.com/sites/default/files/Plockton%20biomass%20CaseStudy_0.pdf

- [14] AEA (2011) A study into the recovery of heat from power generation in Scotland <http://www.scotland.gov.uk/Resource/Doc/917/0121526.pdf>
- [15] Webb (2015) Improving innovation in UK urban district heating: the convergence of social and environmental agendas in Aberdeen, Energy Policy, 78 (2015), pp. 265–272; <http://dx.doi.org/10.1016/j.enpol.2014.12.003>
- [16] Energy Saving Trust (2015) District Heating Loan Fund Evaluation <http://www.energysavingtrust.org.uk/scotland/businesses/getting-support/district-heating-loan>
- [17] DECC, RHI Deployment Data: December 2014 <https://www.gov.uk/government/statistics/rhi-and-rhpp-deployment-data-december-2014>
- [18] Doug Oughton, Steve Hodgkinson (2008) Faber & Kell's Heating & Air-conditioning of Buildings <https://books.google.co.uk/books?id=sPHSChL2mgMC>
- [19] Scottish Government (2012) Scottish House Condition Survey: Energy Use in the Home <http://www.scotland.gov.uk/Topics/Statistics/SHCS/EnergyUse2012>
- [20] DECC Research Report (2013) 'Homeowners' Willingness To Take Up More Efficient Heating Systems' <https://www.gov.uk/government/publications/the-future-of-heating-meeting-the-challenge>
- [21] DECC (2013) The future of heating: meeting the challenge <https://www.gov.uk/government/publications/the-future-of-heating-meeting-the-challenge>
- [22] DECC (2014) Annual Fuel Poverty Statistics Report 2014 <https://www.gov.uk/government/statistics/annual-fuel-poverty-statistics-report-2014>
- [23] Scottish Government (2013) Electricity Generation Policy Statement <http://www.gov.scot/Topics/Business-Industry/Energy/EGPS2012/EGPS2013>
- [24] WWF Scotland (2015) Pathways to Power: Scotland's route to clean, renewable, secure electricity by 2030 <http://assets.wwf.org.uk/downloads/pathwaystopower.pdf>
- [25] Strachan, N., Kannan, R., (2008) Hybrid modelling of long-term carbon reduction scenarios for the UK. Energy Economics 30 (6), 2947–2963.
- [26] G. Anandarajah and W. McDowall, What are the costs of Scotland's Climate and renewable policies? Energy policy, Vol. 50, November 2012, Pp.773–783
- [27] Committee on Climate Change (2014) Reducing Emissions in Scotland: 2014 progress report <http://www.theccc.org.uk/publication/reducing-emissions-in-scotland-2014-progress-report/>
- [28] Energy Research Partnership (2011) The future role for energy storage in the UK <http://erpuk.org/project/energy-storage-in-the-uk/>
- [29] Energy Research Partnership (ongoing) Managing Flexibility of the Electricity System, <http://erpuk.org/project/managing-flexibility-of-the-electricity-sytem/>
- [30] Scottish Government (2013) Low Carbon Scotland; Meeting The Emissions Reduction Targets 2013-2027 <http://www.scotland.gov.uk/Publications/2013/06/6387/downloads>
- [31] Scottish Government (2015) The Heat Policy Statement: Towards Decarbonising Heat: Maximising the Opportunities for Scotland <http://www.gov.scot/Publications/2015/06/6679>
- [32] Watson, J., Gross, R., Ketsopoulou, I. and Winskel, M. (2014). UK Energy Strategies Under Uncertainty - Synthesis Report (UKERC) <http://www.ukerc.ac.uk/publications/uk-energy-strategies-under-uncertainty.html>

2 Technologies and applications

Storing thermal energy needs materials in which to store the energy, and processes for transferring the energy into and out of the material. Section 2.1 below describes the materials, and then Section 2.2 considers how these are applied in TES technologies which allow the effective transfer of heat into and out of the materials.

2.1 Materials

Thermal energy storage stocks thermal energy by heating or cooling a storage medium so that the stored energy can be used at a later time for heating and cooling applications or even power generation. The storage medium is a crucial item for any thermal energy storage technologies as it determines the heat capacity and heat exchange method of the storage system. Currently there are three approaches for the storage medium, namely 1) sensible storage material; 2) phase change material; and 3) thermo-chemical material.

2.1.1 Sensible storage material

Sensible thermal storage materials store thermal energy by raising (heat storage) or reducing (cold storage) their temperature. The amount of stored thermal energy in a mass of material is equal to the product of its specific heat capacity and the temperature change. A container/insulation layer is required to retain the storage material and also to prevent losses of thermal energy. Thus, for sensible thermal storage material it is desirable to have high specific heat capacity, compatibility with its containment, long term stability under thermal cycling and, most importantly, low cost [1].

2.1.1.1 Solid storage material

In general only solid materials and liquid materials can be used as sensible thermal storage media as gaseous materials require extremely large volume containers due to the low density [2-4]. The most commonly used solid materials are rocks, metals, concrete, sand, bricks etc., with their thermal properties listed in [Appendix 1](#) [5, 6]. They can be used for both heat storage and cold storage with a very wide working temperature, since these materials will not freeze or boil. Moreover, these solid materials do not leak from the container and as a result have little effect on the environment.

Solid storage materials can only be used to form passive storage systems which have an additional heat transfer fluid (HTF) to pass through for charging and discharging [7]. The HTF carries energy received from the energy source to the storage medium during charging, and receives energy from the storage when discharging. These systems are also called regenerators. In a regenerator the HTF temperature decreases for heat storage and increases for cold storage during discharging as the solid material cools down for heat storage and warms up for cold storage. In other words, the charging and discharging processes are unsteady [8].

The thermal energy exchange process between the solid storage material and HTF is key to the performance of the regenerator. Both direct contact and indirect contact methods have been developed for the design of regenerators. One direct contact example is the packed bed (e.g. Pebble bed) which consists of a properly insulated container with solid storage material elements remaining packed; see Figure 8 (a) [5, 9, 10].

An example of the indirect contact regenerator is the concrete thermal storage reservoir which is a full concrete structure with pipe circuit laid into, similar to a tubular heat exchanger that integrated into the solid storage material; see Figure 8(b) [12]. Such a regenerator demands a significant share of the investment costs in pipes. The design of the geometry parameters, e.g. tube diameter and number of pipes, is also important for its performance [7].

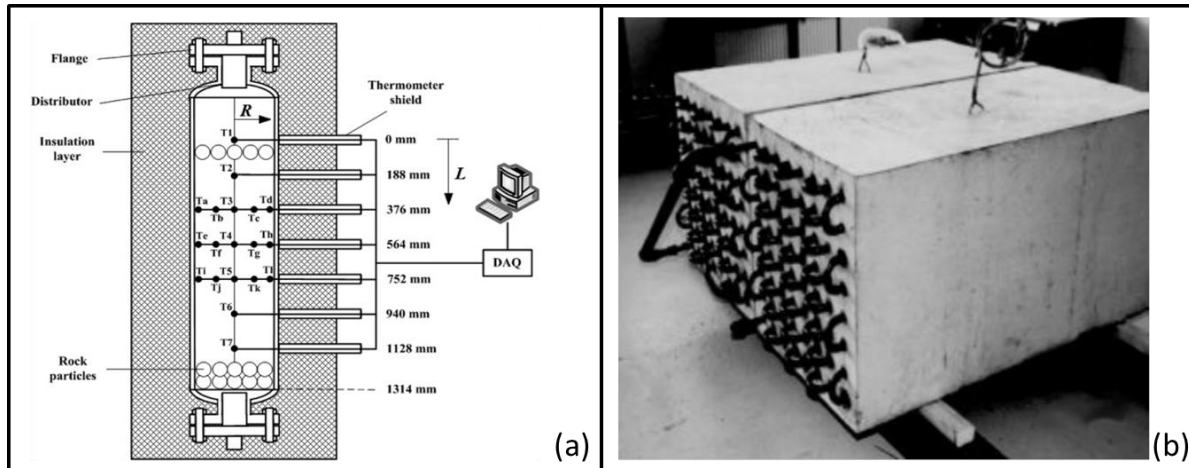


Figure 8 Solid thermal storage material based regenerators: (a) direct contact packed bed; and (b) indirect contact tube-concrete regenerator.

2.1.1.2 Liquid storage material

The commonly used liquid storage materials are water, salty water, oil based fluids, molten salts etc., with their thermal properties listed in Appendix 1 [7]. Different to the solid storage materials, liquid storage materials can only work between its freezing point and boiling point. Liquid storage material itself can be used as a HTF to circulate through heat exchangers in charging/discharging process so that an active storage system is generally formed. As a result the thermal conductivity is a very important thermal property for liquid storage material.

The most commonly used configuration for liquid storage materials is the two tanks direct system that stores the hot liquid and cold liquid in two different tanks, as illustrated in Figure 9(a) [13]. In the charging process the cold liquid is pumped to a heat exchanger to absorb the thermal energy and then into a hot tank that stores the heated liquid. In the discharging process the hot liquid is pumped back to the heat exchanger to release the heat energy and then the cooled liquid is stored in the cold tank. Again for cold storage the system operates in reverse.

The use of liquid storage materials for both transferring and storing thermal energy can greatly simplify the design of the system in that no additional heat exchangers will be needed. Moreover, the operating strategy can be much more straightforward – the amount of cold energy and the objective temperature can be easily adjusted by controlling the flow rate of the fluids [14, 15]. This is extremely difficult to achieve using solid storage materials. The disadvantages are the very high-risk of solidification of the liquid if its freeze point is high (e.g. molten salts), and relatively small temperature difference in heat exchangers which requires large heat exchange surface areas, which will increase the capital cost.

In some cases the two tanks system can be replaced by a single tank system where hot and cold storage liquids are stored in the same tank, as illustrated in Figure 9(b) [16-18]. Here the hot and cold storage liquids are separated because of the stratification, and the zone between the hot and cold fluids is called the thermocline. The thermocline storage system features the hot fluid on top and the cold fluid on the bottom. Usually a filler material is used to help the thermocline effect. And such a configuration can provide one possibility for further reducing the cost of a two tanks system.

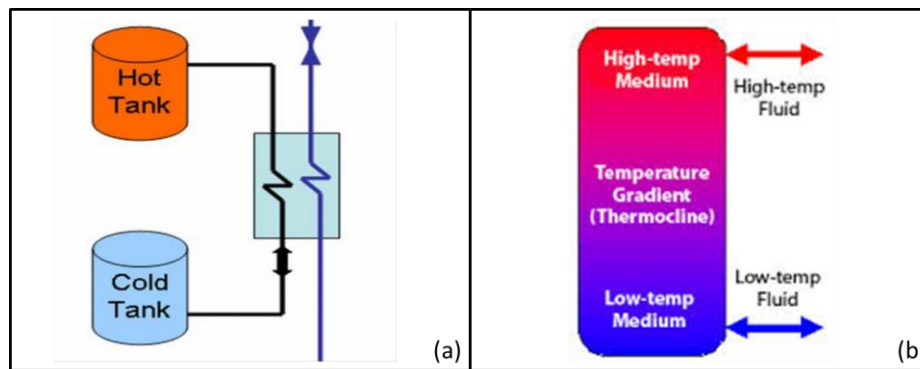


Figure 9 Configurations of liquid material based thermal storage systems: (a) two-tanks; and (b) single-tank system.

2.1.2 Phase change material

Compared to sensible thermal storage described in the previous section, more energy can be stored in a given volume by heating a material which melts or boils (changes phase) at a specific ‘transition’ temperature.³ These are commonly called phase-change materials, PCMs, with the energy released or captured during the phase change called ‘latent heat’. (By contrast, sensible heat storage materials stay in the same phase – generally as a liquid or solid.)

The current PCMs undergo solid–solid, solid–liquid, or liquid–gas phase transformations and they are briefly compared in Table 5.

Phase transformation	Latent heat	Volume change	Advantages/disadvantages
Solid-solid	Small	Very small	Only crystalline state changes, no liquid flow
Solid-liquid	Large	Small	Flow in liquid state
Liquid-gas	Very large	Very large	Large volume in gaseous

Table 5 Comparison of different PCMs

2.1.2.1 Solid-solid PCMs

The crystal structure of solid-solid PCMs will change from one type to another during energy charging/discharging processes so that the latent heat can be used for thermal storage [19]. Many solids undergo reversible phase changes in the solid state, but only very few have sufficient latent heat to be a potential latent heat storage material. Some high density polyethylenes have a solid–solid transition latent heat close to those of melting, yet retain their shape [20].

Generally solid-solid PCMs are of relatively low latent heat. However, several advantages of solid-solid phase transformations such as simpler design for material storage requirement, small erosion, no leakage, no additional storage container for encapsulation and longer lifespan make them worth exploring [21, 22]. Similar to solid sensible materials, solid-solid PCMs can be used in direct contact heat transfer arrangements such as a honeycomb structure with the PCM partially filled to eliminate the requirement for expensive metallic surfaces [7, 23].

2.1.2.2 Solid-liquid PCMs

Solid–liquid PCMs are practically useful because they store a relatively large quantity of heat over a narrow temperature range, without a corresponding large volume change. In fact, most of the solid-

³ As water changes phase at 0°C from solid (ice) to liquid water, and 100°C from liquid water to gas (steam).

liquid PCMs use the sensible heat in the solid and liquid phases and additionally the latent heat due to a phase change during melting or freezing of the storage medium. The melting point is a key parameter for the selection of PCMs in a specific application. The most common PCM is water, which can be used to store cooling power by turning it into ice. A large number of other materials have been reported in temperature ranges suitable for heating or cooling applications and they can be classified into [24, 25]:

- Organic compounds, which are comprised of paraffin and non-paraffin, as listed in Appendix 2 - Organic substances with potential use as PCMs with their thermal properties. In general paraffin PCMs are non-corrosive, chemically inert and stable below 500°C [3, 26]. They show little volume changes but are not compatible with plastic or flammable materials. Therefore they have to be packaged in a suitable container for practical applications. By contrast non-paraffin organic PCMs include a wide variety of organic materials such as fatty acids, esters, alcohols and glycols. They exhibit excellent melting/freezing characteristics without any super-cooling but their cost is generally three times greater than paraffin.
- Inorganic compounds, which include salt hydrates, salts, metals and alloys, as listed in Appendix 3 [27], Appendix 4 [28, 29] and Appendix 5 [29] with their thermal properties. Salts and salt hydrates have a high latent heat of fusion in a given volume, and a small volume change on melting. They are also compatible with plastics and are non-flammable. But they are slightly toxic and corrosive to most metals. Metals and alloys have a very high heat of fusion per unit volume, present higher thermal conductivities and a relatively low vapour pressure.

Like the solid sensible storage materials, the solid-liquid PCMs can only be used to form passive storage systems. The three basic components in such a passive system are the PCM, the container for holding the PCM and the heat exchanging surface for transferring heat from/to the heat source to the PCM. Typically the thermal energy exchange between the PCMs and HTF is processed indirectly, as shown in Figure 10 (a) [30]. However PCMs can also be used to form a direct contact packed bed storage unit if they are packed in a certain shape (e.g. sphere) to increase the heat transfer area, as shown in Figure 10 (b) [31], but this has some technical challenges and a high initial cost.

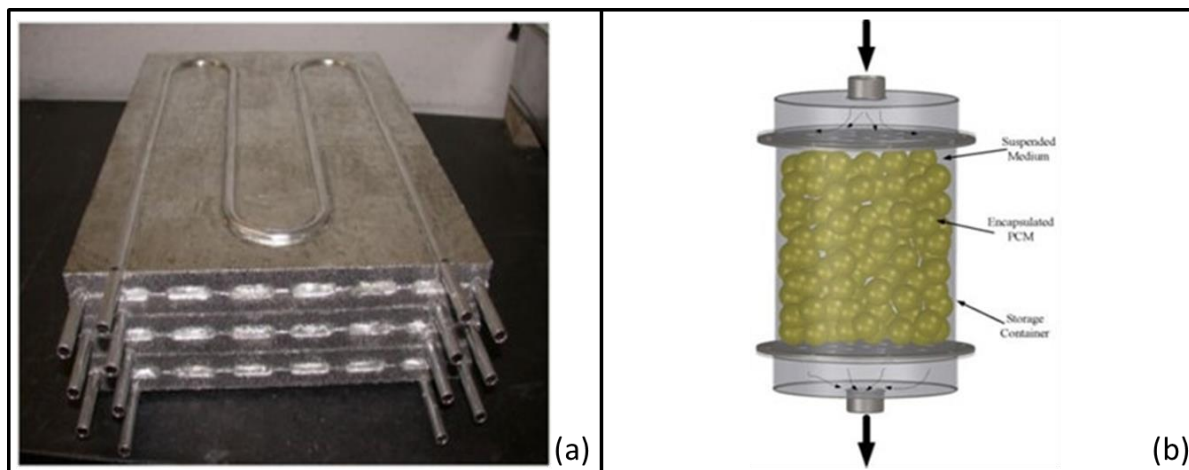


Figure 10 Configurations of PCM based thermal storage systems: (a) Tube-shell system; and (b) PCM encapsulated packed bed.

2.1.2.3 Liquid-gas PCMs

The liquid–gas phase change usually has a high latent heat, but a large volume change means they are not usually considered for practical application. However if the material is simply air, this becomes feasible as only liquid phase material has to be stored. Liquid air energy storage (LAES) uses liquid air as a special PCM [32-34], but is used to store electrical energy rather than thermal energy.

2.1.3 Thermo-chemical material

Thermal energy can also be stored by means of chemical reactions. Chemical reactions always give off heat or soak up heat. If the chemical reaction of a pair of materials is completely reversible, in other words if the released heat can be recovered completely by the reverse reaction, the material can be regarded as thermo-chemical material (TCM) [35]. The commonly used thermo-chemical materials are metal chlorides, metal hydrides, and metal oxides [36].

The advantages of thermo-chemical storage are the high storage energy densities, small heat loss and long storage duration at near ambient temperature, and heat-pumping capability. These properties make it attractive in longer-term storage such as seasonal thermal storage. However thermo-chemical storage systems are complicated compared with sensible and latent storage systems and have a very high capital cost. The development of reversible thermo-chemical storage is still at a very early stage, and costs can be expected to come down.

2.1.4 Comparison of different thermal storage materials

Overall, sensible storage materials have low energy densities (tens to a few hundreds of kJ/kg) and hence the storage system are very bulky; PCMs have much higher energy densities (hundreds to over a thousand kJ/kg) and TCMs could have the highest energy density.

With respect to cost, sensible storage materials are the cheapest among all thermal storage materials (can be below ~£5/kWh), followed by PCMs (generally below ~£50/kWh), and TCMs are the most expensive (can exceed ~£100/kWh).

In terms of current development, sensible storage materials are well developed and have already been widely used in various industrial sectors; PCMs are less developed with a limited number of demonstration and applications; and TCMs are least developed with few applications so far.

2.2 Technologies and applications

As described in Section 1.2, TES can draw on, and provide, both heat and electricity. This section first considers the provision of heat/cold at large and small scales, then electricity, from TES applications which use the materials described above.

In the context of TES technologies, ‘large-scale’ is considered here as those applications in neighbourhoods, industrial sites and cities or regions, which could be for space heat, hot water or process heat. ‘Small-scale’ is that of a single domestic property, providing space heat or hot water. Whilst units of distributed small-scale TES may individually have little effect on the energy system, with smart controls they can be aggregated over millions of homes to have a much larger impact.

2.2.1 For large-scale thermal applications

2.2.1.1 Seasonal heat storage

Seasonal heat storage is one of the possible solutions to meet the winter space heating demand with summer solar radiation or other heat resources. This technology is desirable in particular at higher latitudes, where space heating is necessary and greatest in the cold months when solar energy is

limited. The challenge of seasonal heat storage is the large amounts of energy that are demanded (as described in section 1.3.4.1) and therefore great storage volume required. For such long periods, only low temperature heat storage in underground sites is really feasible and cost-effective.

Until now only the use of water or soil/solid rock as sensible heat storage media has been investigated and demonstrated. Figure 12 [47] illustrates a number of system configurations. In general, hot-water heat stores and aquifer heat stores use water as the storage medium, duct heat stores use the solid soil as the storage medium, while gravel-water heat stores use the combination of liquid water and solid gravel as the storage medium. As the heat capacity of water is larger than solid materials, hot-water and aquifer heat stores have the highest heat storage density, followed by the gravel-water heat stores, while the duct heat stores have the lowest heat storage density [48]. As the aquifer heat store requires a 'two-tank' system, it is considered to be best suited for high temperature and high capacity storage.

Thermal insulation is key to the performance of seasonal heat storage. Even for the hot-water store, the tank construction (usually reinforced concrete) is partly embedded into the ground. The hot-water and gravel-water stores have to be artificially insulated at least on the vertical walls and the top areas. The duct and aquifer heat stores, on the other hand, primarily use natural thermal insulation.

Apart from heat storage density, capital cost is also critical for the deployment of seasonal heat storage. Figure 12 [48] shows the investment costs (per equivalent water storage volume) of the four main configurations using both realised project and planned project data (where filled markers represent realised projects and empty markers represent projects that were only modelled). Preliminary results suggest that larger systems cost less per equivalent storage capacity than small systems; and aquifer storage should be more economically attractive while water tanks should be less.

We also considered the use of water as latent heat storage with phase change materials in seasonal heat storage. However most research is at a very early stage and little has been published. Furthermore seasonal heat storage is always coupled with heat pump technology to meet end-users' heat requirements [49].

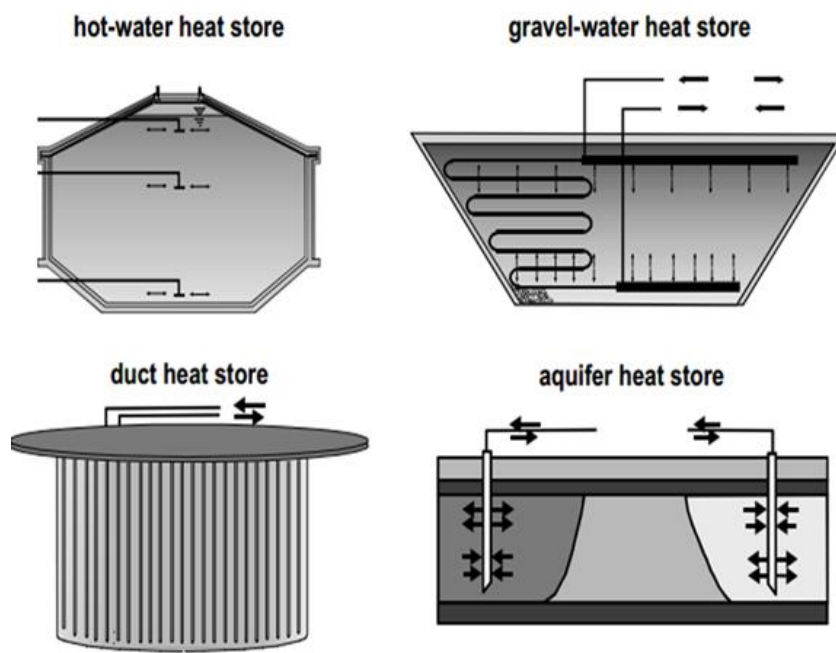


Figure 11 Types of seasonal heat storage

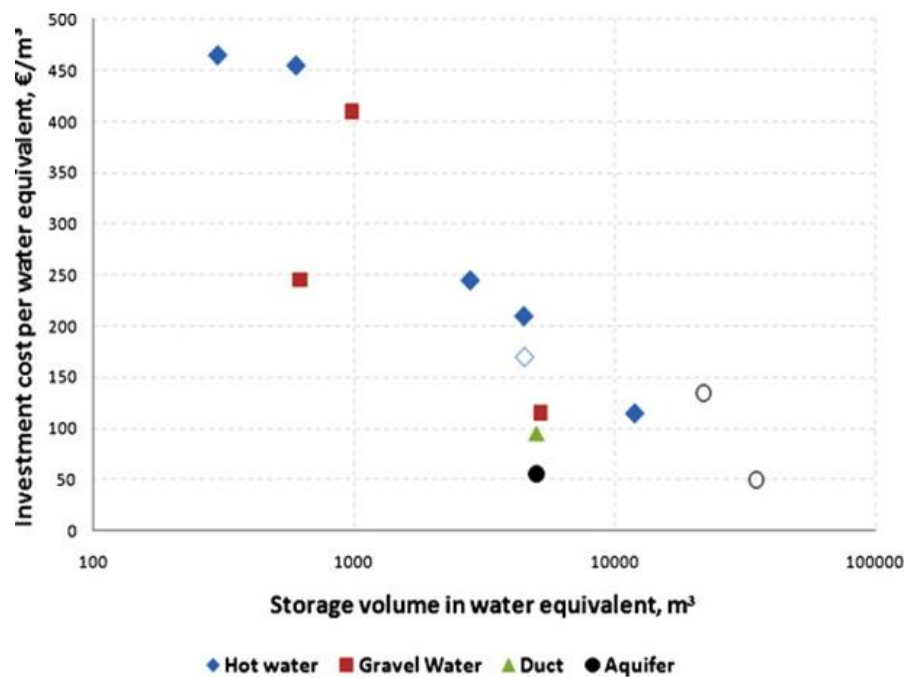


Figure 12 Seasonal heat storage investment costs

2.2.1.2 Thermal storage in CHP/CCHP

Combined heating and power (CHP) and combined cooling, heating, and power (CCHP) as distributed energy supply systems are more and more widely valued because of their potential to reduce cost, primary energy use, and emissions [54]. However, the high fuel efficiency of CHP/CCHP is offset by a lower flexibility because the heat and electricity production cannot be adjusted independently. In principle, the electrical energy can be delivered to consumers over long distances through the electrical grid so the CHP/CCHP system can be run to meet the thermal demand, and the electricity which is then generated can be exported if not required in the locality. However the mismatch between demand for heat and electricity can mean the units would be switched on and off frequently, with a likely negative effect on both energy efficiency and system lifetime.

Thermal energy storage can decouple electricity and heat generation in order to increase the performance of CHP/CCHP system, in particular in cases where the thermal demand is strongly time-varying or discontinuous. The operational principles of such a system are shown in Figure 13 [55]. The CHP/CCHP system operates at its nominal power continuously. When heat demand is greater than the amount of the cogenerated heat, the excess heat requirement can be met first by the heat store, and then by an auxiliary boiler.

It should be noted that thermal storage is only practical if the cogenerated heat/cold accounts for a large share of the end-users' demand. To date, most research is at the feasibility stage and few researchers have discussed the details of TES materials and structures in such applications. We found no thoroughgoing case studies or demonstrations in the literature.

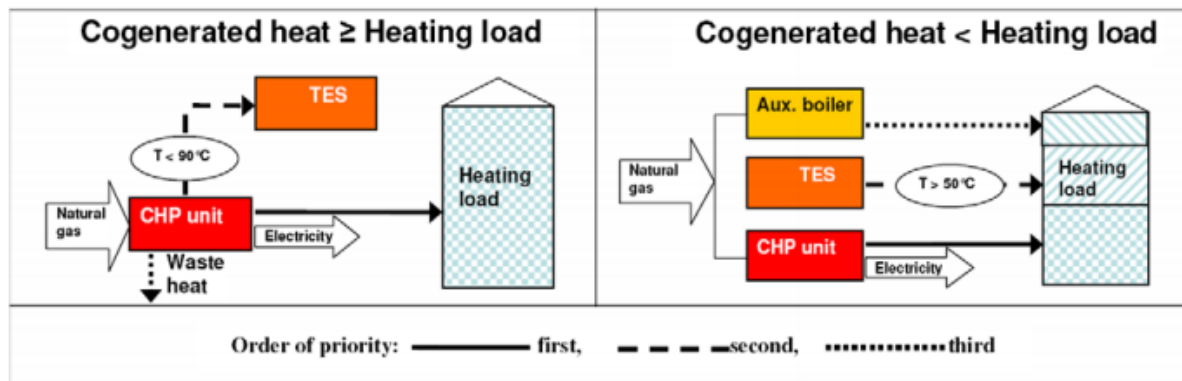


Figure 13 Operational scheme of the CHP-TES system

2.2.1.3 Chilled Water/Ice storage for cooling

Chilled Water/Ice storage is a proven technology for the daily peak shaving of the electricity demand for cooling power generation in summer. Cheap chilled water/ice can be made overnight when the demand for electricity is low, and in the middle of the day, the regular air conditioner can be shut off and instead piping a stream of coolant from the slowly warming water or melting block of ice can meet the end-users' cooling demand until the water warms up to the room temperature or the entire ice blocks have melted and warmed up. In such a way the chiller size can be reduced and the electricity consumption at peak periods (generally afternoon hours) can be shifted to off-peak hours (midnight) when the electricity is more plentiful and less expensive.

Chilled water/ice storage uses water as the storage medium with high heat capacity and/or a high latent heat (about 335kJ/kg). In comparison, ice storage has a larger cooling capacity, lower space requirement, and lower thermal losses to the surrounding environment due to the smaller surface area. The ice storage system can be either a static process, in which heat transfer takes place via a solid surface, or a dynamic process, in which the heat transfer medium and storage medium are in direct contact, whereas the chilled water itself can be used as the heat transfer fluid in a dynamic process. Ice slurries which can be regarded as the combination of chilled water and ice storage have attracted a lot of attention recently as they can be pumped directly through distribution pipe works and heat exchangers [50-52]. Of course the related research is at an early stage and more engineering information is required on fluid flow and heat transfer characteristics for industrial scale applications.

Chilled water/ice storage is widely developed and deployed in particular in United State for electricity bill management and electrical energy time shifting in summer. [Appendix 6](#) [53] lists the current large scale (>100kW) cold storage projects.

2.2.2 For small-scale application

2.2.2.1 Heat storage in solar-water based domestic heating systems

Traditionally, water is used directly as the heat storage medium in solar-water heating system. However PCMs are more promising due to their operational advantages of smaller temperature fluctuation, smaller size and lower weight per unit of storage capacity. Whereas with large-scale applications the focus is on capital cost, unit size and controllability are the dominant factors in household applications. Moreover the operational temperature is low (generally below 50°C) and as a result the packaging and siting of PCMs is technically very simple.

Figure 14 [56] shows an example of a passive solar water-heating system and its PCM based heat storage unit. The well-insulated cylindrical galvanized steel heat storage tank is adopted as the heat

storage unit and the small polyethylene bottles which contain PCM were filled into the tank. The configuration is like a PCM encapsulated packed bed which enables large heat transfer area during the melting and solidification of PCM.

Paraffin is the most popular PCM that has been investigated experimentally in the application of solar-water domestic heating [57, 58]. However at present, the cost of PCM based heat storage is still quite high and as a result application is still mainly restricted to research or demonstration projects.

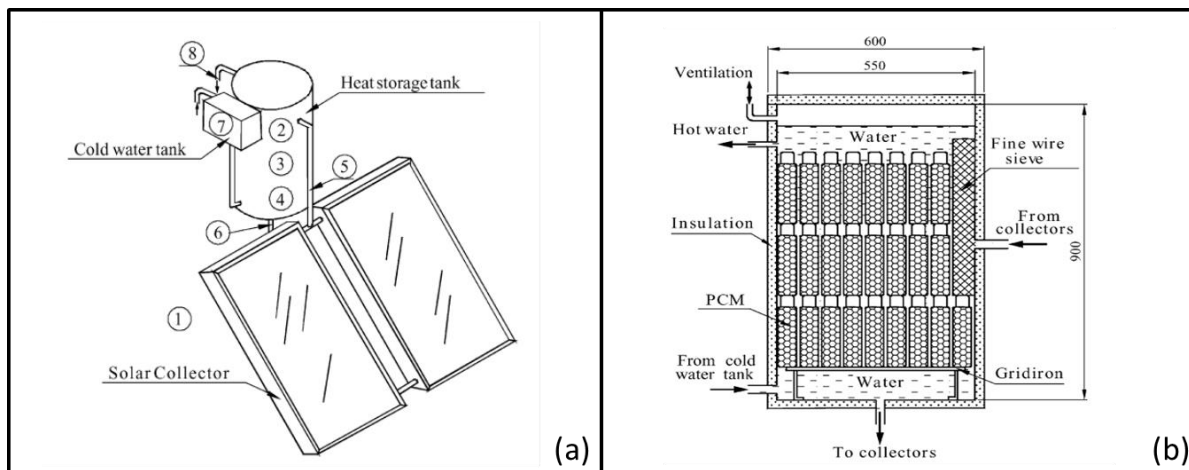


Figure 14 A passive solar water-heating system (a) and its PCM based heat storage unit (b)

2.2.2.2 Thermal storage in building applications

The technical challenge of packaging (or ‘encapsulating’) PCM is the inadequate surface area for heat exchange. However in building applications (commercial or residential) the walls and ceilings can offer large areas for passive heat transfer within every zone. As a result different methods of impregnating gypsum wallboard and other architectural materials with PCM have been investigated. These include: 1) wallboards impregnated with PCMs, 2) concrete blocks impregnating with PCMs, and 3) underfloor heating integrating with PCMs [59]. Comparing with micro-encapsulation or macro-encapsulation, the impregnation method encapsulates PCMs into a structure directly and therefore enables a very simple manufacturing process.

Although limited experimental studies of PCM wallboard have been conducted, the recent investigation can conclude that a PCM wall is capable of capturing a large proportion of the solar radiation incident on the walls or roof of a building [59]. Because of the high thermal mass of PCM walls, they are also capable of minimizing the effect of large fluctuations in the ambient temperature on the inside temperature of the building. It can also provide thermal storage that is distributed throughout a building, enabling passive solar design and off peak cooling with frame construction. The most important point is that little or no additional cost would be incurred for installation of PCM wallboard in place of ordinary wallboard.

2.2.3 For grid-scale electricity

The response times of TES materials mean they are not normally suitable for applications to supply electricity over very short timescales (in ‘seconds’ as described in Table 4).⁴ However, thermal energy storage can be used for the longer duration flexibility requirements. The main available grid-scale thermal energy storage technologies include cryogenic energy storage, solar thermal heat storage, and pumped heat electricity storage. Thermal energy storage is also a key component for improving the efficiency of the electricity storage technology ‘Adiabatic Compressed Air Energy Storage’ (A-CAES), as heat is produced and required during the process [37, 38].

2.2.3.1 Cryogenic energy storage

Cryogenic energy storage (CES), also known as liquid air energy storage (LAES), uses liquid air as the storage medium for electrical energy storage. The principle is shown in Figure 15(a) [39]. A cryogen (e.g. liquid nitrogen or liquid air) is produced using off-peak power or renewable generated electricity. When electricity is needed, heat from the surrounding environment boils the liquid, the heated cryogen in the form of a rapidly expanding gas is used to generate electricity using a cryogenic heat engine. Other TES materials are used in the CES process, illustrated in Figure 15(a), to improve its efficiency to around 60%.

A particular advantage of the technology is the ability to use excess heat (from the flue gas of the power plant, or industrial process, as examples) to warm the cryogen when generating electricity. This gives a much higher power output, and is an efficient use of low-temperature (100°C or less) heat, normally considered as ‘waste’. This can raise the effective efficiency to over 80%.

CES can use existing infrastructure for the air liquefaction and gas sectors. The technology has no geographical constraints and does not need the use of any exotic materials. CES has a relatively long storage duration (hours to weeks) and a relatively short response time (~2.5 min is achievable). It has a high cycling ability with a life span estimated at 25-60 years and minimal degradation in terms of depth-of-discharge. Full CES systems work economically at large scales (tens of MWs) using current technology: for a 50MW/200MWh unit, the cost is estimated at £1000/kW, £250/kWh [41].

CES is currently in the pre-commercial stage, with the UK having an internationally leading position in its innovation. Research Councils have funded the world’s first research institute, the Birmingham Centre for Cryogenic Energy Storage, to accelerate R&D with a 350kW/2.5MWh full pilot plant (Figure 15(b)); and the Department for Energy and Climate Change is funding a 5MW/15MWh demonstrator being built by Highview Power Storage Ltd, a UK based company, near Manchester.

⁴ When TES materials are used in suitable technologies, they can capture energy in these short timescales as sources of demand. For example, an immersion coil in a hot-water tank can be switched on, and instantaneously capture excess electricity by heating the water.

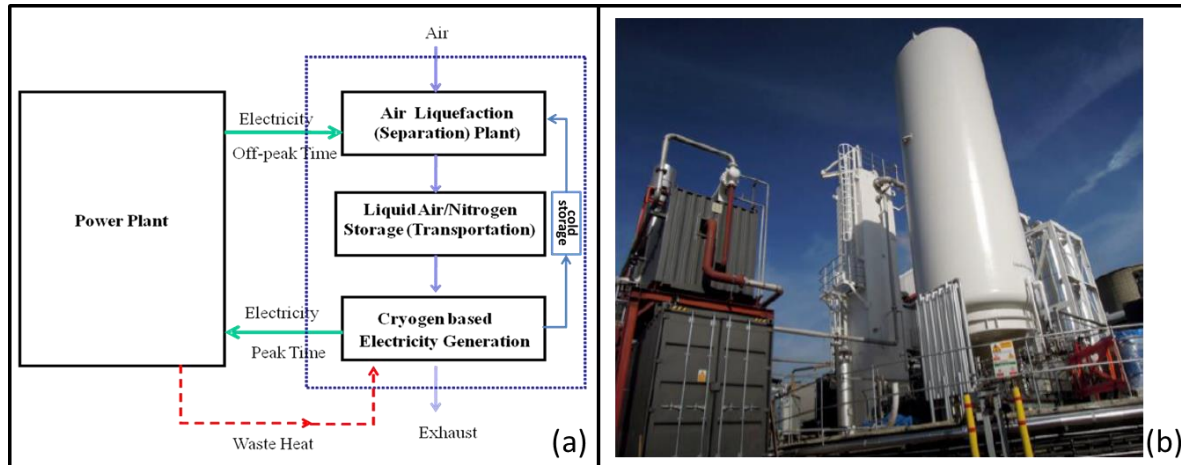


Figure 15 Cryogenic energy storage system : (a) Schematic principles; and (b) pilot plant (350kW/2.5MWh)

2.2.3.2 Solar thermal heat storage for power generation

Currently, commercially available thermal energy storage technology plays a significant role in extending the operation of concentrating solar power (CSP) plants. To date, over 40% of all commercial CSP plants have integrated TES systems. Most of them use a two-tank molten salt system (as shown in Figure 16 (a) [7]) while single-tank system with stratification of the molten salts has also been demonstrated. Apart from liquid molten salt, solid material based sensible heat storage, for example using ambient air as heat transfer fluid and stones/rock as storage medium (as shown in Figure 16(b)), has also been studied and demonstrated [42].

However, there are still some technical challenges in CSP thermal storage systems, in particular the molten salt system. In molten salt storage systems a huge amount of salt has to be kept at temperatures above the melting point (120 to 240°C, depending on their composition). Keeping the salts in liquid state in the piping of the solar field consumes significant amount of energy during the night and during periods of lack of sun or maintenance and as a result reduces the overall efficiency. Melting the salt for the first time uses external energy. In addition, the tanks, pumps, heat exchangers, piping and valves react with the salts resulting in corrosion that can interfere with the operation of the CSP plant.

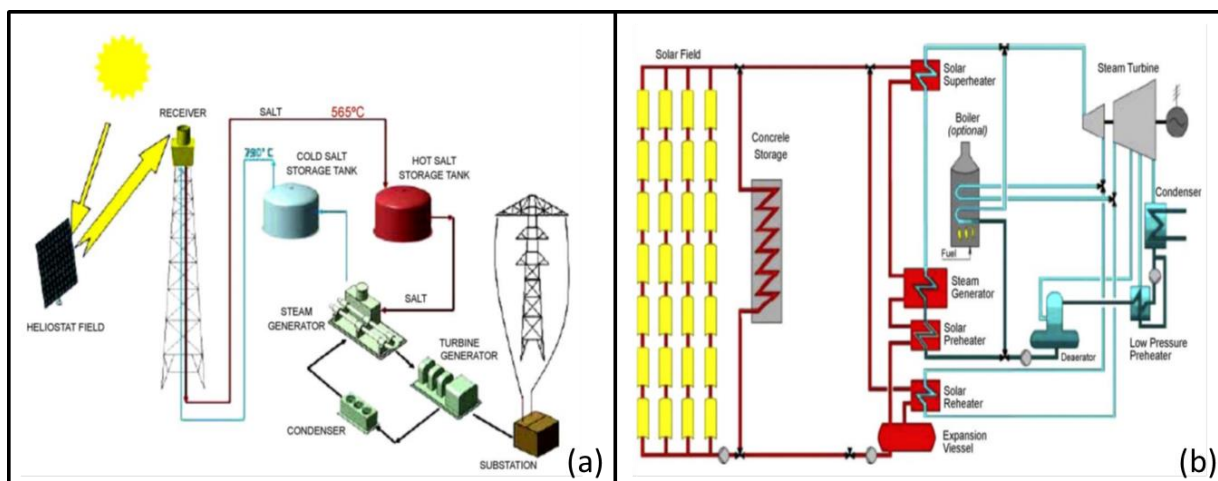


Figure 16 Schematic diagrams of a CSP plant with: (a) two-tanks thermal storage system; and (b) concrete thermal storage system

2.2.3.3 Pumped heat electricity storage

Pumped Thermal Electricity Storage (PTES) is based on well-established heat pump and heat engine mechanisms (reversible) coupled with heat and cold storage, as shown in Figure 17 [43, 44]. For grid scale applications, the technology requires storage of both heat and cold at high grade for an acceptable level of energy density and round-trip efficiency [45]. The current solutions use sensible heat storage materials, and an inert gas (e.g. argon) to transfer heat across the store. Like CES, PTES has the advantages of not needing a specific geographical location, little environmental impact, favourable volumetric energy density.

Despite being sound in principle, PTES technology is still at the validation stage, going through whole system demonstration at both lab and pilot scales. There are technical challenges to achieving good efficiency, associated with transferring heat across the storage device, and the specialist machinery required. Currently, a UK based company Isentropic and an Italian oil and gas company Saipem [46] are developing the technology. At the heart of their designs are a reversible reciprocating heat-pump/heat-engine, with Isentropic expecting to achieve a round-trip efficiency of 72%. In 2012 they announced a \$22 million investment from the Energy Technologies Institute (ETI) with a short-term goal of deploying a 1.5MW/6MWh system at a levelised cost of storage of \$35/MWh.

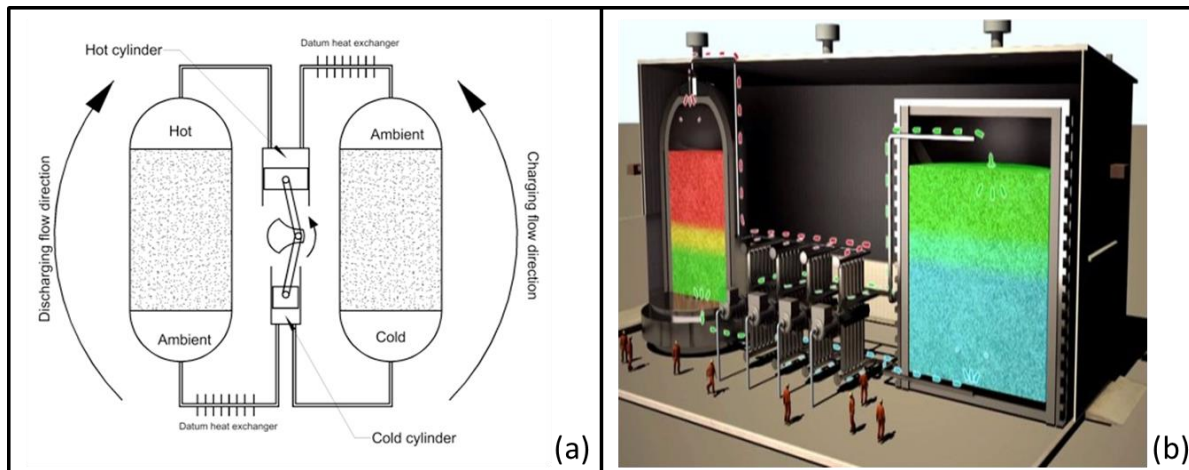


Figure 17 Pumped heat electricity storage system: (a) Schematic principles; and (b) layout of the system

2.3 Summary

A summary of the different thermal storage materials described above, and their technology application, is given in Table 6. Limited information is available on the costs of the technologies, with high level of uncertainties given the early stage of development. This is discussed further in Section 3.3 below.

Thermal Energy Storage materials					Technology application features		
		Sensible heat	Phase change	Thermo-chemical			
	Example materials	Water, gravel, pebble, soil ...	Organics, inorganics ...	Metal chlorides / hydrides / oxides ...			
	Type of TES system	Water-based (water tank, aquifer), rock or ground-based	Packaged in passive storage systems	Adsorption/absorption, chemical reaction, at high temperatures			
Technology applications of TES materials	Seasonal heat	Demonstrated			Use/location	Timescale	Energy scale
	CHP	Commercial			Balancing summer/ winter heat demand	Months	GWh
	Cooling/chilling	Commercial	Deployed		Balancing electrical/heat network demand	Hours - days	10s MWh
	Domestic TES	Commercial	In Development	In Research	Reduction in daily peak; commercial properties	Hours	10s MWh
	Building fabric	Deployed	Demonstrated		Reduction in daily peak; households	Hours	10s kWh
	Cryogenic	Demonstrated	Demonstrated		Reduction in daily peak; Domestic/commercial	Hours	kWh and above
	Solar thermal	In early deployment	In early deployment		Grid integration of variable renewables	Hours – days	10s –100s MWh
	Pumped thermal	In development			Smoothing output from solar thermal	Hours	10s –100s MWh
	Advantages	Environmental, cost, simplicity, reliability	Higher energy density, constant temperature	Highest energy density, low loss for long duration storage	Grid integration of variable renewables	Hours	Up to 10s MWh
	Disadvantages	Low energy density, heat losses, site construction capex	Lack of stability, corrosion, high cost of storage materials	Poor heat transfer, cyclability, high cost of storage material			

Table 6 Comparison of different thermal storage materials. (Blank boxes indicate areas of low activity.)

Section 2 References

- [1] Hasnain SM. Review on sustainable thermal energy storage technologies, Part I: heat storage materials and techniques. *Energy Conversion and Management*. 1998;39:1127-38.
- [2] Regin AF, Solanki SC, Saini JS. Heat transfer characteristics of thermal energy storage system using PCM capsules: A review. *Renewable and Sustainable Energy Reviews*. 2008;12:2438-58.
- [3] Sharma A, Tyagi VV, Chen CR, Buddhi D. Review on thermal energy storage with phase change materials and applications. *Renewable and Sustainable Energy Reviews*. 2009;13:318-45.
- [4] Pasupathy A, Velraj R, Seeniraj RV. Phase change material-based building architecture for thermal management in residential and commercial establishments. *Renewable and Sustainable Energy Reviews*. 2008;12:39-64.
- [5] Singh H, Saini RP, Saini JS. A review on packed bed solar energy storage systems. *Renewable and Sustainable Energy Reviews*. 2010;14:1059-69.
- [6] Dincer I. Thermal energy storage systems as a key technology in energy conservation. *International Journal of Energy Research*. 2002;26:567-88.
- [7] Gil A, Medrano M, Martorell I, Lázaro A, Dolado P, Zalba B, et al. State of the art on high temperature thermal energy storage for power generation. Part 1—Concepts, materials and modellization. *Renewable and Sustainable Energy Reviews*. 2010;14:31-55.
- [8] Singh R, P. SR, Saini JS. Models for Predicting Thermal Performance of Packed Bed Energy Storage System for Solar Air Heaters – A Review *The Open Fuels & Energy Science Journal*. 2009;2:6.
- [9] Mawire A, McPherson M, Heetkamp RRJvd, Mlatho SJP. Simulated performance of storage materials for pebble bed thermal energy storage (TES) systems. *Applied Energy*. 2009;86:1246-52.
- [10] Chai L, Liu J, Wang L, Yue L, Yang L, Sheng Y, et al. Cryogenic energy storage characteristics of a packed bed at different pressures. *Applied Thermal Engineering*. 2014;63:439-46.
- [11] Chandra P, Willits DH. Pressure drop and heat transfer characteristics of air-rockbed thermal storage systems. *Solar Energy*. 1981;27:547-53.
- [12] Laing D, Bahl C, Bauer T, Lehmann D, Steinmann W-D. Thermal energy storage for direct steam generation. *Solar Energy*. 2011;85:627-33.
- [13] Herrmann U, Kelly B, Price H. Two-tank molten salt storage for parabolic trough solar power plants. *Energy*. 2004;29:883-93.
- [14] Li Y, Cao H, Wang S, Jin Y, Li D, Wang X, et al. Load shifting of nuclear power plants using cryogenic energy storage technology. *Applied Energy*. 2014;113:1710-6.
- [15] Li Y, Wang X, Jin Y, Ding Y. An integrated solar-cryogen hybrid power system. *Renewable Energy*. 2012;37:76-81.
- [16] Pacheco JE, Showalter SK, Kolb WJ. Development of a Molten-Salt Thermocline Thermal Storage System for Parabolic Trough Plants. *Journal of Solar Energy Engineering*. 2002;124:153-9.
- [17] Brosseau D, Kelton JW, Ray D, Edgar M, Chisman K, Emms B. Testing of Thermocline Filler Materials and Molten-Salt Heat Transfer Fluids for Thermal Energy Storage Systems in Parabolic Trough Power Plants. *Journal of Solar Energy Engineering*. 2005;127:109-16.
- [18] Liu M, Saman W, Bruno F. Review on storage materials and thermal performance enhancement techniques for high temperature phase change thermal storage systems. *Renewable and Sustainable Energy Reviews*. 2012;16:2118-32.
- [19] Li W-D, Ding E-Y. Preparation and characterization of cross-linking PEG/MDI/PE copolymer as solid–solid phase change heat storage material. *Solar Energy Materials and Solar Cells*. 2007;91:764-8.
- [20] Su J-C, Liu P-S. A novel solid–solid phase change heat storage material with polyurethane block copolymer structure. *Energy Conversion and Management*. 2006;47:3185-91.

- [21] Wang X, Lu E, Lin W, Liu T, Shi Z, Tang R, et al. Heat storage performance of the binary systems neopentyl glycol/pentaerythritol and neopentyl glycol/trihydroxy methyl-aminomethane as solid–solid phase change materials. *Energy Conversion and Management*. 2000;41:129-34.
- [22] Sari A, Alkan C, Biçer A, Karaipekli A. Synthesis and thermal energy storage characteristics of polystyrene-graft-palmitic acid copolymers as solid–solid phase change materials. *Solar Energy Materials and Solar Cells*. 2011;95:3195-201.
- [23] Felix Regin A, Solanki SC, Saini JS. An analysis of a packed bed latent heat thermal energy storage system using PCM capsules: Numerical investigation. *Renewable Energy*. 2009;34:1765-73.
- [24] Farid MM, Khudhair AM, Razack SAK, Al-Hallaj S. A review on phase change energy storage: materials and applications. *Energy Conversion and Management*. 2004;45:1597-615.
- [25] Py X, Olives R, Mauran S. Paraffin/porous-graphite-matrix composite as a high and constant power thermal storage material. *International Journal of Heat and Mass Transfer*. 2001;44:2727-37.
- [26] Bal LM, Satya S, Naik SN. Solar dryer with thermal energy storage systems for drying agricultural food products: A review. *Renewable and Sustainable Energy Reviews*. 2010;14:2298-314.
- [27] Zalba B, Marín JM, Cabeza LF, Mehling H. Review on thermal energy storage with phase change: materials, heat transfer analysis and applications. *Applied Thermal Engineering*. 2003;23:251-83.
- [28] Haiyan LI JL. Revolutionizing heat transport enhancement with liquid metals: Proposal of a new industry of water-free heat exchangers. *Front Energy*. 2011;5:20-42.
- [29] Wee AG, Schneider RL, Aquilino SA. Use of low fusing alloy in dentistry. *The Journal of Prosthetic Dentistry*. 1998;80:540-5.
- [30] Agyenim F, Hewitt N, Eames P, Smyth M. A review of materials, heat transfer and phase change problem formulation for latent heat thermal energy storage systems (LHTESS). *Renewable and Sustainable Energy Reviews*. 2010;14:615-28.
- [31] Ismail KAR, Stuginsky Jr R. A parametric study on possible fixed bed models for pcm and sensible heat storage. *Applied Thermal Engineering*. 1999;19:757-88.
- [32] Li Y. *Cryogen Based Energy Storage: Process Modelling and Optimisation*. Leeds: University of Leeds; 2011.
- [33] Li Y, Chen H, Ding Y. Fundamentals and applications of cryogen as a thermal energy carrier: A critical assessment. *International Journal of Thermal Sciences*. 2010;49:941-9.
- [34] Li Y, Chen H, Zhang X, Tan C, Ding Y. Renewable energy carriers: Hydrogen or liquid air/nitrogen? *Applied Thermal Engineering*. 2010;30:1985-90.
- [35] De Maria G, D'Alessio L, Coffari E, Paolucci M, Tiberio CA. Thermochemical storage of solar energy with high-temperature chemical reactions. *Solar Energy*. 1985;35:409-16.
- [36] Xu J, Wang RZ, Li Y. A review of available technologies for seasonal thermal energy storage. *Solar Energy*. 2014;103:610-38.
- [37] Jakiel C, Zunft S, Nowi A. Adiabatic compressed air energy storage plants for efficient peak load power supply from wind energy: the European project AA-CAES. *International Journal of Energy Technology and Policy*. 2007;5:296-306.
- [38] Hartmann N, Vöhringer O, Kruck C, Eltrop L. Simulation and analysis of different adiabatic Compressed Air Energy Storage plant configurations. *Applied Energy*. 2012;93:541-8.
- [39] Chen H, Cong TN, Yang W, Tan C, Li Y, Ding Y. Progress in electrical energy storage system: A critical review. *Progress in Natural Science*. 2009;19:291-312.
- [40] Li Y, Wang X, Ding Y. An optimal design methodology for large-scale gas liquefaction. *Applied Energy*. 2012;99:484-90.
- [41] Strahan D. Liquid Air in the energy and transport systems: Opportunities for industry and innovation in the UK. In: CLCF, editor. 2013.

- [42] Schneider G, Maier H. Status of the Development of a New High Temperature Thermal Energy Storage System (HTTESS) for CSP-power Plants. *Energy Procedia*. 2014;49:965-72.
- [43] Howes J. Concept and Development of a Pumped Heat Electricity Storage Device. *Proceedings of the IEEE*. 2012;100:493-503.
- [44] White A, Parks G, Markides CN. Thermodynamic analysis of pumped thermal electricity storage. *Applied Thermal Engineering*. 2013;53:291-8.
- [45] White AJ. Loss analysis of thermal reservoirs for electrical energy storage schemes. *Applied Energy*. 2011;88:4150-9.
- [46] Desrues T, Ruer J, Marty P, Fourmigué JF. A thermal energy storage process for large scale electric applications. *Applied Thermal Engineering*. 2010;30:425-32.
- [47] Schmidt T, Mangold D, Müller-Steinhagen H. Central solar heating plants with seasonal storage in Germany. *Solar Energy*. 2004;76:165-74.
- [48] Pinel P, Cruickshank CA, Beausoleil-Morrison I, Wills A. A review of available methods for seasonal storage of solar thermal energy in residential applications. *Renewable and Sustainable Energy Reviews*. 2011;15:3341-59.
- [49] Wang X, Zheng M, Zhang W, Zhang S, Yang T. Experimental study of a solar-assisted ground-coupled heat pump system with solar seasonal thermal storage in severe cold areas. *Energy and Buildings*. 2010;42:2104-10.
- [50] Bellas J, Chaer I, Tassou SA. Heat transfer and pressure drop of ice slurries in plate heat exchangers. *Applied Thermal Engineering*. 2002;22:721-32.
- [51] Saito A. Recent advances in research on cold thermal energy storage. *International Journal of Refrigeration*. 2002;25:177-89.
- [52] Egolf PW, Kauffeld M. From physical properties of ice slurries to industrial ice slurry applications. *International Journal of Refrigeration*. 2005;28:4-12.
- [53] DOE. DOE Global Energy Storage Database.
- [54] Mago PJ, Luck R. Evaluation of a base-loaded combined heating and power system with thermal storage for different small building applications. *International Journal of Energy Research*. 2013;37:179-88.
- [55] Pagliarini G, Rainieri S. Modeling of a thermal energy storage system coupled with combined heat and power generation for the heating requirements of a University Campus. *Applied Thermal Engineering*. 2010;30:1255-61.
- [56] Canbazoglu S, Şahinaslan A, Ekmekyapar A, Aksoy ÝG, Akarsu F. Enhancement of solar thermal energy storage performance using sodium thiosulfate pentahydrate of a conventional solar water-heating system. *Energy and Buildings*. 2005;37:235-42.
- [57] Fazilati MA, Alemrajabi AA. Phase change material for enhancing solar water heater, an experimental approach. *Energy Conversion and Management*. 2013;71:138-45.
- [58] Kenisarin M, Mahkamov K. Solar energy storage using phase change materials. *Renewable and Sustainable Energy Reviews*. 2007;11:1913-65.
- [59] Khudhair AM, Farid MM. A review on energy conservation in building applications with thermal storage by latent heat using phase change materials. *Energy Conversion and Management*. 2004;45:263-75.

3 Implementation

The potential of energy storage has only recently been recognised by many countries, especially as the deployment of solar/wind has increased. It is also seen as having a role in delivering more flexible energy systems in the face of increasing demand and access to electricity, growing urbanisation, security of supply considerations, or physical infrastructure requiring reinforcement. As such, energy storage technology innovation programmes are still in the early stages, and understanding of how TES could be deployed is evolving.

Heat has often been viewed as the Cinderella of the energy system, and likewise electricity storage has been the focus of most early research in energy storage. Advances in batteries have been driven by application in (and market for) consumer electronics and electric vehicles, but there has been less attention paid to thermal storage. Although a small number of groups and companies have been developing TES for some time, it is an area where the capacity and capability needs to grow if its potential is to be realised.

In this section, the TES technology development activity in Scotland is described, and the barriers to deployment of energy storage (which apply equally to TES) are set out. Innovation across science, engineering, policy and business models will be required for the technologies to be deployed at scale.

3.1 Technology innovation in Scotland

3.1.1 Research

The UK Energy Research Centre (UKERC) has published an Energy Storage Research Landscape.[1] Three groups in Scotland were identified:

- School of Mathematical and Computer Science, Heriot-Watt University: Mathematical foundations for energy networks
- School of Chemistry, University of St Andrews: Lithium batteries
- Chemical and Process Engineering, University of Strathclyde: hydrogen storage, EV batteries

We interrogated Gateway to Research[2], which holds records of projects from Research Councils and Innovate UK, with the terms *Thermal “energy storage”* for programme funding being undertaken in Scotland, and filtered by inspection to find projects relevant to this report.[3]

14 projects, with total value £11.2m were found to be active (i.e. with end date in 2015 or later), although few had TES as a primary subject. Since 2010, 45 projects have been funded with a total value of £18.5m.

The Energy Technology Partnership has identified specialist energy research centres in Scottish universities[4]. Each was searched for work related to thermal energy storage, with the following being most relevant:

University of Edinburgh

The University of Edinburgh hosts ‘Heat and the City’, a project funded by the UK Research Councils for multi-disciplinary research addressing a major gap in UK sustainable energy policy, which is the neglect of energy used for heating and hot water in buildings. <http://www.heatandthecity.org.uk/>

University of Strathclyde

Energy Systems Research Unit, Department of Mechanical & Aerospace Engineering: works with SSE on the NINES project (see below). <http://www.strath.ac.uk/esru/>

Chemical and Process Engineering: The Low Carbon Technology research theme aims to develop innovative solutions to the global problem of carbon dioxide emissions, including carbon capture, novel methods for storing and generating energy, and efficient processing.

- Hydrogen storage
- Network Support using electric vehicle batteries

<http://www.strath.ac.uk/chemeng/research/lowcarbontechnology/>

Heriot-Watt University, Edinburgh

Centre for Advanced Energy Storage and Recovery (CAESAR): Led by Professor Anthony Powell, is an interdisciplinary centre for materials research.

Principal research areas include thermoelectric power generation, supercapacitors, catalysts, carbon capture, chemical looping, hydrogen storage materials, diamond films, polymeric materials, superconducting materials, and gas hydrates.

<http://www.energy.hw.ac.uk/research/resResearch.cfm?eaResearchArea=advEnergyMat>

Low Carbon Buildings: Professor Sue Roaf, also in the School of the Built Environment, has research interests include the emerging field of Low Carbon Building design incorporating issues of passive building performance, efficient technology and building integrated renewable energy generators.

Scottish Institute for Solar Energy Research (SISER): Researchers at Heriot-Watt University and the UK Astronomy Technology Centre are working on the integration of storage by directly illuminating a thermal store with concentrated solar radiation. The thermal store performs a dual function of providing heat for a Stirling engine and storing thermal energy for when there is little or no solar irradiation. Direct absorption in the store eliminates the parasitic load required by other concentrating solar thermal systems to pump a working fluid between the receiver and the heat engine. Computational modelling is also being undertaken to investigate the potential of different materials to be used as thermal energy stores. <http://siser.eps.hw.ac.uk/index.php/research/solar-thermal/high-solar-thermal-energy>

University of Glasgow

Systems, Power and Engineering, School of Engineering: Thermal management is important in improving the overall efficiency of processes which deliver renewable electrical power. Research is underway on the use of thermoelectric and thermoacoustic processes for diverse applications e.g low-energy thermoacoustic refrigeration and thermoelectric harvesting of excess heat on solar panels to complement diurnal storage and improve the efficiency of photovoltaic processes.

<http://www.gla.ac.uk/schools/engineering/research/divisions/systems/researchthemes/energy/>

3.1.2 Demonstration projects

The energy regulator Ofgem has supported projects sponsored by the Distribution Network Operators (DNOs) through its Low Carbon Networks Fund (LCNF) to try out new technology, operating and commercial arrangements. This scheme finished in March 2015, after which the Network Innovation Competition (NIC) will award up to £27m annually for electricity transmission companies to compete for funding for the development and demonstration of new technologies, operating and

commercial arrangements. A project funded by the UK Energy Research Centre (UKERC), being undertaken by Prof Jan Webb at the University of Edinburgh, is analysing local energy systems, drawing on the experiences of past LCNF projects. [5]

Several LCNF projects have been awarded which include TES elements:

Northern Isles New Energy Solutions (NINES) project

SHEPD is working with Shetland Islands Council and Hjaltland Housing Association to install advanced storage heating and water heating in around 750 existing homes (see Figure 18). These new storage and water heaters (which will replace existing traditional storage heaters) are being provided through SIC, Hjaltland and ERDF funding and have been specifically designed to use a much more flexible electrical charging arrangement.

Shetland Heat Energy and Power (SHEAP) is proposing to extend the existing Lerwick district heating scheme by installing a 4MW electrical boiler, which will be linked to a new thermal store capable of storing around 130MWh of hot water. The existing district heating scheme is currently supplied by waste heat from the islands waste to energy plant and also relies on significant quantities of oil to meet the requirements of the scheme.

<http://www.ninessmartgrid.co.uk/our-trials/>

<http://www.smarternetworks.org/Project.aspx?ProjectID=403>

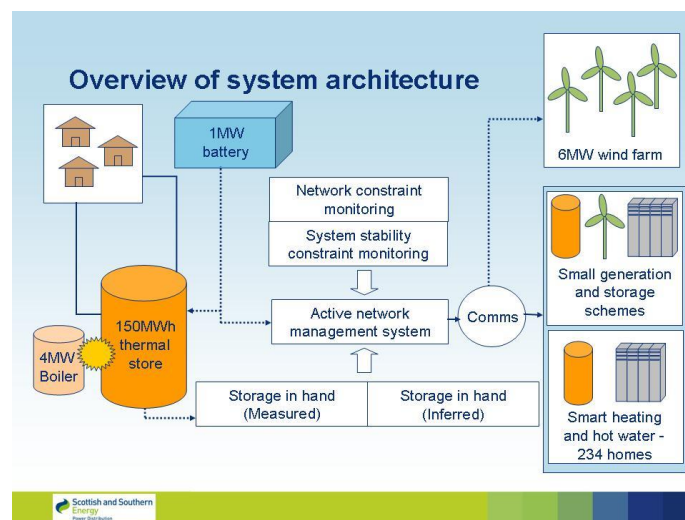


Figure 18 NINES project overview

A trial evaluation of domestic demand side management in Lerwick involved partnership working with Glen Dimplex to develop and trial a new range of domestic energy efficient storage heaters and immersion water heaters (hot water cylinders) designed for grid energy storage, demand side management and frequency response. In addition to these network benefits, the design was projected to benefit customers by providing a more efficient and controllable heating system.

Some research on the basis of the Shetland projects is now being published. Clarke et al at the University of Strathclyde have found that “domestic electric storage heaters operating within a smart grid offer high density, controllable energy storage at low cost, allowing the network operator to shift demand by charging heaters to dispose of excess supply.”[6]

By monitoring space and water heating patterns on Shetland, the group found that space heaters had 35 – 40% (or less) of their capacity used; whilst hot water storage had 50 – 70% utilisation. Power was drawn outside scheduled hours 20% of the time for space heaters, and up to 70% of the time for water heaters. The research found a complex interaction of central, heater and occupant controls.

Other projects

The Scottish Government's Local Energy Challenge fund has awarded a £3.2m grant to a project led by Sunamp Ltd to demonstrate the benefit of local heat storage and the value of integrated renewable energy solutions. 'Reducing Fuel Poverty: Heat Storage Innovation' [7] will develop and implement 'heat batteries' in communities in Lothian and Falkirk.

We found other energy storage demonstration projects, without specific thermal energy storage relevance, including:

- DECC Energy Storage Technology Demonstration Competition, Gigha: Project for the demonstration and pre-commercialisation of a 1.26MWh utility scale system of grid scale flow battery technology.[8]
- Orkney Energy Storage Park: to create a commercial contract to incentivise the third party energy storage providers.[9]
- Flexible Networks for a Low Carbon Future, SP Distribution: network management and operation[10]

3.2 Deployment case studies

This section gives case studies of innovative examples showing the potential of integrating TES into energy systems: two examples of large-scale TES combined with solar thermal energy generation, and one example of TES integrated into a city-scale heat network.

3.2.1 Sensible thermal energy storage for district heating infrastructure (Turin, Italy)

Background

Turin has the largest Italian district heating network (DHN), with about 450 km network length operated by Iren[11]. It supplies heat to nearly 50% of buildings and 500,000 citizens, with an overall thermal capacity of almost 1,800 MW, of which 750 MW is by combined heat and power (CHP) generation. The district heating infrastructure is supported by three thermal energy storage systems (one is under development) with a total capacity of 725MW_{th} (12,500m³ hot water).

Technology

Pressurized (18 bar) liquid water at 120°C is stored in insulated tanks with a storage volume of 1000m³ each. Thermal energy is stored daily during the night, when heat demand is low and it is used to peak shave the heating demand profile during the morning (6-8 a.m.) when maximum thermal power is required by the network infrastructure (Figure 19). This allows increased usage of the CHP asset and reduced backup boiler installation and operation. In the scenario study, it has been shown that the capacity of back-up boilers can be reduced from 990MW to 680MW with a total storage volume of 10,000m³. The optimal storage size is estimated to be ~ 30,000 m³ bringing a reduction of fuel consumption around ~ 100 GWh (12% reduction).

Economic performance

Iren is the owner of the whole DHN system including heat network, CHP, heat storage and heat-only boilers. The benefits of the heat storage are not easy to quantify/verify in Turin due to a lack of available data from the company. Personal communications reveal that the TES systems presents a

total investment cost of about 2500 €/m³. Total annual costs (investment and operation) are about 55 M€/year for optimal storage size. Also, the electricity production during the working days increases by about 22GWh. The addition of heat storage increased capital costs by 5-20% but has enabled reliable and cost-effective heat supply.

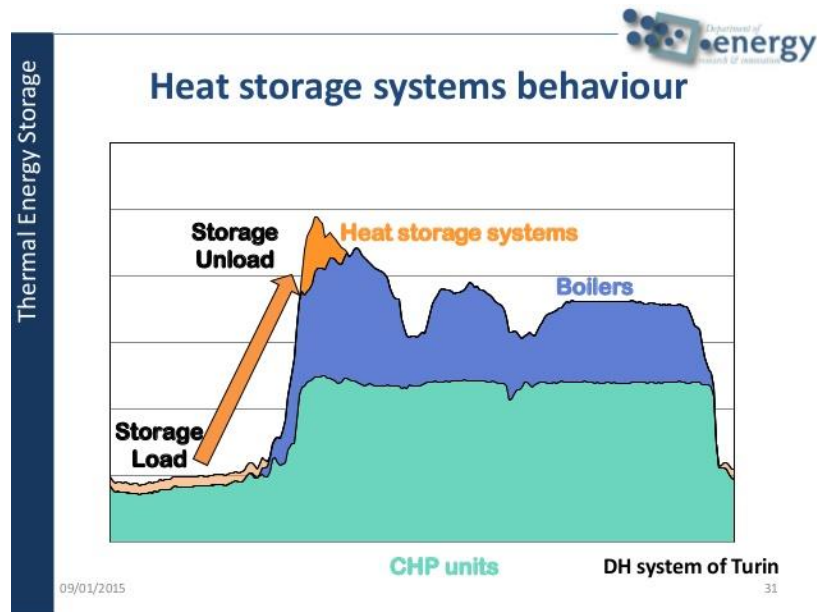


Figure 19 Illustration of peak shaving by thermal storage in Turin heat network.[12]

3.2.2 Underground thermal energy storage – Drake landing community storage, Canada

Background

The Drake Landing Solar Community (DLSC) is a 52-home subdivision that uses the sun's energy to supply 90% of space-heating and up to 60% of domestic hot water needs[13]. A district heating system has been designed to store solar energy using a seasonal thermal energy storage system. An array of 800 solar panels located on garage roofs throughout the community generate 1.5 MW of thermal power during a typical summer day and supply heat to the district heating system. The excess heat is stored underground via boreholes and returned to the homes during winter season (Figure 20). The project received support from an Alberta-based natural gas distribution company, ATCO gas. Until the solar heating system began working, ATCO Gas fixed heating costs at \$60 per month for the homeowners. Had the project failed, ATCO Gas would have replaced the special hot-water furnaces with traditional natural gas ones. As a result there was limited risk to the homeowners and this encouraged them to support the project.

Technology

The borehole thermal energy storage (BTES) system stores thermal energy by exploiting the ground as a heat sink. The BTES consists of 144 boreholes that stretch for 37 meters below the ground and cover an area 35 metres in diameter. Initially, the BTES requires a few years to be fully charged, and subsequently is fully charged by the end of the summer, increasing the ground temperature to 80 °C. In the second year of operation, the system provided only about 60% of the heating energy from collected solar energy with the remainder being provided by a natural gas boiler. This percentage rose to 97% by the end of 5 years (and is expected to stay at that level) as the ground was slowly heated up and the long-term storage became more effective.[14]

Economic performance

DLSC is a project to assess the feasibility of a solar energy community system. Initial start-up capital of \$7 million for the Drake Landing system included \$2 million from federal government agencies, \$2.9 million from the Federation of Canadian Municipalities – Green Municipal Investment Fund and \$625,000 from Albertan government agencies. Today, the housing division is sold out and homeowners are paying, on average, a \$60 per month solar utility bill for heating. A full economic assessment has not yet been published.

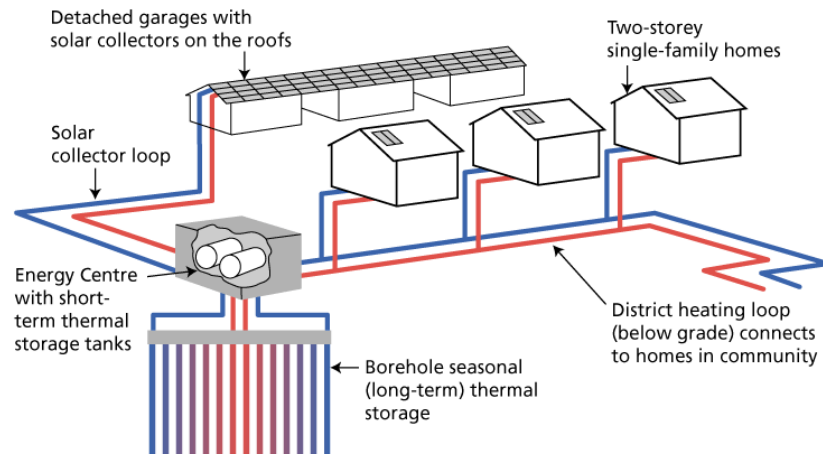


Figure 20 Schematic diagram of Drake Landing Solar Community Borehole Thermal Energy Storage and district heating System (from <http://www.dlsc.ca/how.htm>).

3.2.3 Marstal district heating system - Denmark

Background

Large scale seasonal pit heat storage in Marstal, Denmark is a key part of the 'SUNSTORE 4' project[15]. The overall objectives of the project are to demonstrate an energy concept of a large scale innovative cost efficient, and technical reliable 100% renewable energy supply system for a large scale district heating system with yearly heating production of 28,000 MWh - based on 55% solar thermal energy and 45% biomass based CHP.

Technology

The SUNSTORE 4 project boasts 75,000 m³ of newly constructed heat storage by PBJ Miljø which is seven times larger than the previous one, with an energy volume of 6,960 MWh.[16] It consists of a huge water-filled basin lined with high-density polyethylene covered with foil. The cover foil is made of a new material, which contains polyethylene foam and a high-density polyethylene lining. It is designed to reduce heat losses at the top side by 60 % compared to the small existing storage. It was soldered from 2 m wide stripes. The expected lifespan is 20 years at a maximum temperature of 80 °C, which is the limit for the storage space.

Economic performance

This is a demonstration project which was financially supported by the EU with €6.1 million for the whole Marstal's district heat plant. The pit storage cost €2.7 million excluding transmission pipes, equivalent to 35.5 €/m³ or 0.38 €/kWh.



Figure 21 Marstal solar collectors and pit storage (circled) (from <http://sunstore4.eu/newsroom/events-presentations/>)

3.2.4 Lessons learned from case studies

Large scale thermal energy storage is still at the early stage with most projects financially supported by public funds. Large scale thermal energy storage demonstration is also a long-term activity which may take several years or even decades to show the real value. As a result the concrete benefits of large scale heat storage are not easy to quantify/verify. However the comparison of the studied cases indicates some important aspects:

- **Ownership:** the heat storage system is not an isolated sector and generally other generation sectors will benefit from the addition of heat storage with improved performance. Therefore it seems in a real business case the ownership of the heat storage system should be combined with the ownership of energy generation infrastructure.
- **Heat resources:** the heat storage system can be used to balance fossil fuel based heat generation and supply or to maximize the utilization of renewable heat resources. In general conventional heat supply can make use of existing heat supply network and as a result is more promising in the near future.
- **Capacity scales:** Again the capacity scale of the heat storage system depends heavily on the heat supply network. Making use of the existing heat supply network can enable city or even larger scale application while otherwise the community/neighbourhood scale might be the best option.
- **Time scales:** In general when combined with CHP the heat storage will operate on a daily basis, whilst for renewable energy utilization seasonal heat storage may be required. Providing heat for a day's use requires less energy to be stored than for an entire season, so a smaller store with lower capital cost is needed. At the same time, the daily store is being utilised more frequently with more opportunities to extract value, rather than once a year. The economic performance of shorter time-scale storage is thus better than for longer time-scales.

3.3 Costs

The costs of energy storage are normally presented in terms of either the investment required (£/kW to install a system), or to supply energy (£/kWh, using the levelised cost of energy, LCOE[17]). Financial assessment of energy storage presents two key challenges

- Uncertain technology costs: with many TES technologies in development and not yet commercialised, estimates of costs will have high levels of uncertainty
- Uncertain/variable value: the net cost of energy being stored in a TES device is a function of both the price paid on charging, and earned on discharging, both of which are highly dependent on the energy system and the market framework in which the device is operating.

Cost-benefit analyses of different TES technologies in the Scottish system would provide a better quantification of the real costs, but Table 7 Indicative TES costs

TES principle	Storage system costs (€/kWh)[18]	TES technology	Initial investment cost (USD/kW)[19]
Sensible heat	0.1 – 10	Underground TES	3 400 - 4 500
		Pit storage	100 – 300
		Solid media	500 – 3000
		Cold water	300 – 600
Phase change	10 – 50	Molten salt	400 – 700
		Ice	6000 – 15000
Thermochemical	8 - 100	Thermochemical	1000 – 3000

Table 7 Indicative TES costs

3.4 Barriers to deployment

A number of reports [20, 21, 22, 23, 24] have highlighted barriers to the deployment of energy storage in the UK. These have tended to focus on electrical energy storage, though some aspects are relevant to how TES technologies would also be deployed, especially if used in an application with electricity. Subsections below present the barriers, and how TES may be affected in particular.

3.4.1 Technology cost and performance

The current price of some energy storage technologies is too great to give a business model for deployment, even if the full system value could be extracted. The materials used in manufacturing some phase change and thermochemical technologies in particular can be expensive and difficult to handle, adding to the costs. Increasing cyclability (which measures how often a material can charge/discharge energy) is important, especially for PCMs which undergo structural changes as they absorb or release heat. Research programmes (including those funded by EPSRC in the UK) are investigating new materials and manufacturing processes to reduce costs and improve performance.

TES technologies could provide multiple services (as set out in Table 4) and therefore in principle, be able to attract revenue from more than one source, across timescales of seconds to days. A business model which captures those income streams is difficult to establish, both for a potential business and the market in which it will operate, as the technology will cut across traditional business boundaries.

3.4.2 Markets

The current market framework may not allow the true value of energy to be reflected in the price – price volatility, which exposes times of scarcity and hence an opportunity for TES to exploit through arbitraging, is not generally welcomed by Governments. Very high spikes or low troughs in wholesale prices resulting from variable renewables will be dampened by the EMR's capacity mechanism and

Ofgem's cash-out balancing market reforms. Retail time-of-use tariffs which could give domestic consumers cheaper prices in periods of low demand or excess supply, and accessed with smart meters, may not be compatible with moves towards simpler energy bills.

New market entrants could bring innovative business models and technologies to work alongside storage, for example balancing supply by using 'smart' systems to aggregate and control distributed TES.

More fundamentally, the future long-term value of storage (as quantified in Reference 22) cannot be recognized in today's market, with the consequence that other established technologies (i.e. thermal generation) crowd-out the space now, but lock-in future emissions.

3.4.3 Regulatory/policy frameworks

There are restrictions on network operators operating storage technologies on a merchant basis. High network charges affect storage operators. It is not clear what impact the EMR process will have for energy storage technologies.

Deployment of TES technologies could also be dependent on other policy initiatives and standards, including the renewal of housing stock and associated infrastructure (such as heat networks) – deployment of different technologies could be more suitable during retrofit or for new build.

3.4.4 Societal

Large-scale deployment of energy storage could introduce new technologies at a local level. Some TES materials could be pervasive, unfamiliar and potentially harmful if not handled properly. Though risks may be low compared to others faced already, new technologies could be rejected if launched on an unsuspecting public without proper engagement. Larger facilities will need planning approval and wider community acceptance if they are to be adopted.

3.4.5 Uncertainty of value

The value of energy storage in general is critically dependent on the nature of the energy system. This presents a barrier when there is uncertainty in how the energy system will evolve, because of technology, policy or finance challenges. For example, if deployment of wind is low (or expected to be low), this could reduce the appetite for investing in options which can mitigate the variability impacts of high wind penetration, such as TES.

Models have so far been limited in their scope and ability to include storage, so to some extent estimates of value under different scenarios are still to be refined. However, we can consider where TES can meet some of the key energy system challenges:

3.4.5.1 Meeting high demand for thermal energy from electrified heating/cooling

The case for large-scale seasonal heat storage in the UK is mainly dependent on the significant electrification of heat, which would require an increase in generation capacity, running at lower load-factors (as described in section 1.3.4.1). The issues are similar for hot/cold TES which operates over shorter timescales, due to variations in weather rather than seasonal temperatures.

Both CHP (or tri-generation) and biomass could grow significantly in Scotland with policy drivers and incentives, hence reduce the requirement for seasonal or domestic TES.

3.4.5.2 Providing efficient community-level heat and power

The efficiency of district heat networks and combined heat and power plants can be compromised when the demand for heat and power is not matched to production, on a diurnal or annual cycle. TES is commonly used in such systems, normally as large hot water stores. Where space is restricted (in city centres for example) there could be a case for using other materials with higher energy

density. A slow take-up of DHN/CHP to meet energy efficiency targets would impact on how TES technologies could be deployed in this application.

3.4.5.3 Integrating variable renewable energy production (in particular wind/solar)

As described in this report, TES technologies can be a very effective mechanism to help balance variable supply from renewables with changing demand profiles. This application of TES is of course dependent on achieving 'high' penetration of renewables, and on the deployment of other technologies which can provide similar flexibility to the energy system. For example, increasing electrical connections to the rest of the GB grid or Norway would impact the need for (and hence value of) TES. Assessing the value of TES under different scenarios requires detailed analysis taking into account Scotland's energy system.

Section 3 References

- [1] <http://ukerc.rl.ac.uk/Landscapes/EnergyStorage.pdf>
- [2] <http://gtr.rcuk.ac.uk/>
- [3] A search term of “thermal energy storage” returns seven projects in the UK, none in Scotland.
- [4] <http://www.etp-scotland.ac.uk/ETPforAcademics/SpecialistCentres.aspx>
- [5] <http://www.ukerc.ac.uk/programmes/energy-systems-at-multiple-scales/local-energy-infrastructure-operation-governance.html>
- [6] Clarke et al (2015) Performance of actively controlled domestic heat storage devices in a smart grid; Proc IMechE Part A: J Power and Energy, Vol. 229(1) 99–110 DOI: 10.1177/0957650914554726. Also see a presentation on the research by Svehla at <http://www.ninessmartgrid.co.uk/wp-content/uploads/2013/06/Home-Space-and-Water-Heating-Aspects-of-the-SSE-Shetland-NINES-Project.pdf>.
- [7] <http://www.localenergyscotland.org/funding-resources/funding/local-energy-challenge-fund/phase-two-projects/reducing-fuel-poverty-heat-storage-innovation/>
- [8] <http://www.redtenergy.com/news/redt-wins-%C2%A336m-decc-award-energy-storage>
- [9] <https://www.ssepd.co.uk/Innovation/CompletedProjects/>;
<https://www.ssepd.co.uk/OrkneySmartGrid/>
- [10] <http://www.smarternetworks.org/Project.aspx?ProjectID=398>
- [11] http://www.irenenergia.it/ChiSiamo/Media/brochure/files/en/Iren_Energia_Teleriscaldamento_Torino_UK.pdf
- [12] Marco Carlo Masoero, Energy storage in urban multi-energy systems, presentation to ICARB workshop, Edinburgh, 21st October 2014, available from <http://www.slideshare.net/icarb/marco-masoero-energy-storage-in-urban-multienergy-systems>
- [13] See <http://www.dlsc.ca/>.
- [14] The performance of a high solar fraction seasonal storage district heating system - Five years of operation, Sibbitt B., McClenahan D., Djebbar R., Thornton J., Wong B., Carriere J., Kokko J. (2012) Energy Procedia, 30, pp. 856-865 <http://dx.doi.org/10.1016/j.egypro.2012.11.097>
- [15] See <http://sunstore4.eu/>
- [16] Morten Vang Jensen (PlanEnergi) ‘Design of pit heat storage’, 2nd International Solar District Heating Conference, June 2014, Hamburg, available from <http://sunstore4.eu/newsroom/events-presentations/>.
- [17] For a treatment of LCOE see DECC (2012) Electricity Generation Costs https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/65713/6883-electricity-generation-costs.pdf
- [18] IEA/IRENA (2013) Thermal Energy Storage Technology Brief; http://www.iea-etsap.org/Energy_Technologies/Energy_Supply/Thermal_Energy_Storage.asp
- [19] IEA Technology Roadmap: Energy Storage, Annex A – Technology Annex (2014) <https://www.iea.org/publications/freepublications/publication/technology-roadmap-energy-storage-.html>
- [20] Energy Research Partnership (2011) The future role for energy storage in the UK <http://erpuk.org/project/energy-storage-in-the-uk/>
- [21] Strbac et al (2012) Strategic Assessment of the Role and Value of Energy Storage Systems in the UK Low Carbon Energy Future <http://www.carbontrust.com/resources/reports/technology/energy-storage-systems-strategic-assessment-role-and-value>
- [22] Strbac et al (2012) Understanding the balancing challenge http://www.decc.gov.uk/en/content/cms/meeting_energy/network/strategy/strategy.aspx
- [23] Centre for Low Carbon Futures (2012) Pathways for Energy Storage <http://www.lowcarbonfutures.org/pathways-energy-storage-uk>
- [24] UKERC (2011) The future of energy storage: stakeholder perspectives and policy implications

4 Conclusions

Scotland's energy system is undergoing radical transformation to meet emissions-reduction targets. Generation will become increasingly variable on the supply side from wind power. The decarbonisation of heat from a mixture of biomass, district heat networks and electrification will shift patterns of use on the demand side. Fundamentally, energy must be considered as a whole system, and the electricity system not treated in isolation.

A more flexible energy system will be needed, with flexible generation, demand side response, greater electrical connectivity to other regions, and energy storage all likely to play a role. Without detailed analysis comparing the options, the mix of technologies cannot be predicted, but a strong case can be made for considering thermal energy storage, in principle, to be an area which naturally balances the changes in supply and demand. Analysis of the UK energy system has shown that energy storage reduces system costs in scenarios with high renewable deployment.

TES technologies do exist which can meet these requirements, but many are at an early stage of development or are yet to be fully commercialised. This is in part due to the costs and performance, and partly due to the non-technical barriers that exist which restrict their integration into the system. The two issues are intertwined – greater certainty in the future value of TES would drive investment into innovation, with the expectation of lowering costs, so that the technologies become more competitive with other options.

Thermal energy storage defines a process, but its application may span electricity and heat sectors. To illustrate this, an 'opportunity matrix', identifying where TES could be applied is shown in Figure 22.

		Supply	
		Heat	Electricity
Demand	Heat	Phase-change materials (salts, paraffin); solid/liquid sensible heat storage (water, concrete, subsurface); thermo-chemical reactions.	
		Waste/surplus heat fed into DHN. Gas/biomass-fired boilers or CHP run at maximum efficiency for heat networks. Domestic hot water from boiler for use when required.	Wrong-time electricity from renewables stored for peak heat demand.
	Electricity	Liquid air energy storage; Compressed air energy storage; Pumped heat electricity storage.	
		Waste/surplus heat converted to electricity for peak electricity demand.	Wrong-time electricity from renewables stored thermally for peak electricity demand. Thermal power stations run at maximum efficiency.

Figure 22 TES technology-opportunity matrix

A major uncertainty when considering the role of TES (and other infrastructure) is the uncertainty in how decarbonised heat will be provided.[1] However, this should not be a reason for inaction, indeed, advances in TES could point to which technologies are best able to provide heat at different scales.

There is a risk that fixes to the energy system, such as new fossil fuel power plants, are put in place, as they are currently available and have the lowest short-term cost. Other options like TES could be better long-term solutions, though requiring some initial investment.

Some priority activities which may be undertaken either by the Scottish Government, or at the UK and EU level with support from Scotland, as appropriate, are:

- Support for development of thermal energy storage materials that can provide more effective domestic heating from electricity.
- Control technologies that allow distributed TES to respond to system signals.
- Testing of seasonal thermal storage.
- Supporting demonstration of near-to-market TES technologies at scale.
- Assessing the policy and regulatory framework for energy storage, to avoid the creation of unintended barriers to deployment.
- Building capacity and capability in TES in Scotland.

Further detail on specific opportunities – and challenges – for Scotland is given below.

TES with heat pumps

The relatively large number of off-gas grid properties in Scotland, which are likely to use oil as a heating fuel, means that there is significant scope to decarbonise heat. Thermal storage is well-suited to supporting domestic renewable heat when delivered by heat pumps – this would avoid peaking effects. However, the trend in Scotland has been to use biomass for domestic renewable heat, as supported by the RHI (in contrast to England). This may be due to lower outdoor temperatures making HPs less efficient, and the greater availability of biomass as a fuel. The scale of opportunity for TES with heat pumps may therefore be lower than in the rest of the UK.

Hot water storage

Across the UK domestic boilers using hot water tanks have been replaced by combi-boilers, which provide instantaneous hot water. Surveys have found that consumers value the additional space highly (more so in smaller properties). Research shows that the efficiency of HW tanks could be improved, and costs reduced, with the use of alternative materials.² Using stainless steel in place of copper increases the time over which useable hot water can be extracted by 50%.

A million hot water tanks, each containing 6kWh of thermal energy, could store energy equivalent to that held in Foyers pumped hydro storage station.[3] With new phase change materials with several times the energy density of water, such distributed storage technologies could be an effective option.

A recent report by the International Energy Agency[4] supports this conclusion, stating

“The cost-effectiveness of distributed thermal storage points to the importance of coupling the electricity sector with other sectors of the energy system to achieve cost-effective [variable renewable energy] integration.”

There may be a case for incentivising, or regulating, the retention of hot water tanks where they still exist.

Electric storage heaters

More effective electrically-driven domestic TES, for Economy 7 storage units, alongside improvements to energy efficiency of buildings, would help meet end-user needs and the requirements for a more flexible energy system. Even 'high heat retention storage heaters', as defined by BRE, lose over half their heat by the time it is needed.[5] New technologies should have:

- higher efficiency and energy density - so that heaters can deliver sufficient thermal comfort to users;
- more sophisticated controls - to take advantage of surplus electricity at times of excess production;
- lower cost - to be economically attractive.

Again, new high energy density TES materials would have a positive impact if they could be produced at the right cost. Supporting research and development into new TES materials for these applications would allow their potential to be better understood and quantified, as well as bringing them closer to market.

Heat networks

District heat networks may be an option for decarbonising heat in some cases, and TES (large hot water accumulators) is routinely used to ensure peak demand is met. For these applications, when space is not at a premium, and the temperature is less than 100°C, water is the obvious storage medium.

However, the temperature range for storing industrial waste heat can be much higher than the boiling point of water, and so new materials could be used to capture such heat for use either in electrical generation (see below) and/or heat networks.

It is worth noting that the EU Energy Efficiency Directive[6] requires cost-benefit analysis for CHP and DHC schemes, so the methods to assess thermal energy storage options should be developed that will allow improved decision-making. Such analysis will also indicate how markets could be designed to recognise wider environmental value of heat networks.

Seasonal TES

The greatest variability in energy demand is that for heat between summer and winter. The current physical storage of natural gas allows this to be managed. However, scenarios envisage heat pumps using low carbon electricity to provide a substantial proportion of domestic heat. If natural gas is to be replaced (even in part) by other fuels such as electricity, generation capacity will need to rise to an appropriate level, with such thermal or renewable plant either not running in the summer or exporting to other demand centres. Alternatively, storing electrical energy over a period of months to provide heat in the winter would in principle be a solution.

Such technologies, such as underground thermal energy storage, do exist but have limited deployment. Given the opportunity, this could be an activity that would be worthwhile testing in Scotland.

TES for electricity

Finally, some TES technologies allow the capture and delivery of electricity, at the same time making effective use of ‘waste’ heat. When Combined Heat and Power is used, there may be periods of operation for electricity generation when excess heat is produced. Many other sources of heat have also been identified in Scotland, and capturing this otherwise ‘waste’ heat to convert into electricity (where there is no local demand for the heat itself), could be done through Liquid Air (or Cryogenic) Energy Storage (LAES), or Pumped-Heat Energy Storage (PHES). LAES has the added benefit of producing a source of cold which is of value including to the food value chain and data centres[7].

Section 4 References

- [1] Eyre & Baruah (2014) Uncertainties in future energy demand in UK residential heating
doi:10.1016/j.enpol.2014.12.030
<http://www.sciencedirect.com/science/article/pii/S0301421514007058>
- [2] P. Armstrong, , D. Ager, I. Thompson, M. McCulloch Improving the energy storage capability of hot water tanks through wall material specification, Energy 78, 15 December 2014, Pages 128–140
<http://dx.doi.org/10.1016/j.energy.2014.09.061>
- [3] Mackay (2008) Sustainable Energy — without the hot air <http://www.withouthotair.com/>
- [4] IEA (2014) Grid Integration of Variable Renewables
<http://www.iea.org/topics/renewables/renewablesiea/renewablesintegrationivar/>
- [5] BRE (2012) The Government’s Standard Assessment Procedure for Energy Rating of Dwellings
http://www.bre.co.uk/filelibrary/SAP/2012/SAP-2012_9-92.pdf p. 26
- [6] Energy Efficiency Directive, 2012/27/EU <http://ec.europa.eu/energy/en/topics/energy-efficiency/energy-efficiency-directive>
- [7] CLCF (2013) Liquid Air Technologies – a guide to the potential
<http://www.birmingham.ac.uk/Documents/college-eps/energy/research/CLCF-LiquidAirTechnicalGuide,October2013.pdf>

Appendix 1 - Properties of sensible heat storage materials

Thermal properties of commonly used solid materials for sensible thermal storage:

Material	Density (kg/m ³)	Specific Heat capacity (kJ/kg·°C)	Volume-specific heat capacity (kJ/m ³ ·°C)	Thermal conductivity (W/m·°C)
Granite	2700	0.80	2200	2.7
Marble	2700	0.88	2400	2.3
Fe ₂ O ₃	5200	0.76	4000	2.9
Al ₂ O ₃	4000	0.84	3400	2.5
Cement	2470	0.92	2300	2.4
Brick	1700	0.84	1400	0.63
Cast	7600	0.46	3500	46.8

For heat storage the energy can be stored by having hot HTF flow from top to bottom and later the stored energy can be retrieved by making flow of cold HTF from bottom to top of the bed, while for cold storage it operates in reverse. The advantage of such a design is that the large heat exchange surface area enables fast and efficient charging/discharging processes. The disadvantage is the contamination of the HTF as well as an elevated working pressure of the packed bed if the working pressure of HTF is high (e.g. high pressure compressed air) [11].

Thermal properties of commonly used liquid materials for sensible thermal storage:

Storage medium	Temperature		Average density (kg/m ³)	Average thermal conductivity (W/m K)	Average heat capacity (kJ/kg K)	Volume specific heat capacity (kWh/m ³)	Media costs/kg (US\$/kWh)	Media costs/kWh (US\$/kWh)
	Cold (°C)	Hot (°C)						
Mineral oil	-10	300	770	0.12	2.6	55	0.30	4.2
Synthetic oil	13	350	900	0.11	2.3	57	3.00	43.0
Silicone oil	-40	400	900	0.10	2.1	52	5.00	80.0
Nitrite salts	250	450	1825	0.57	1.5	152	1.00	12.0
Nitrate salts	265	565	1870	0.52	1.6	250	0.50	3.7
Carbonate salts	450	850	2100	2.0	1.8	430	2.40	11.0
Liquid sodium	270	530	850	71.0	1.3	80	2.00	21.0

Appendix 2 - Organic substances with potential use as PCMs

Compound	Melting temperature (°C)	Heat of fusion (kJ/kg)	Thermal conductivity (W/m K)	Density (kg/m ³)
Paraffin C ₁₄	4.5	165	n.a.	n.a.
Paraffin C ₁₅ –C ₁₆	8	153	n.a.	n.a.
Polyglycol E400	8	99.6	0.187 (liquid, 38.6 °C)	1125 (liquid, 25 °C)
			0.185 (liquid, 69.9 °C)	1228 (solid, 3 °C)
Dimethyl-sulfoxide (DMS)	16.5	85.7	n.a.	1009 (solid and liquid)
Paraffin C ₁₆ –C ₁₈	20–22	152	n.a.	n.a.
Polyglycol E600	22	127.2	0.189 (liquid, 38.6 °C)	1126 (liquid, 25 °C)
			0.187 (liquid, 67.0 °C)	1232 (solid, 4 °C)
Paraffin C ₁₃ –C ₂₄	22–24	189	0.21 (solid)	0.760 (liquid, 70 °C)
				0.900 (solid, 20 °C)
1-Dodecanol	26	200	n.a.	n.a.
Paraffin C ₁₈	28	244	0.148 (liquid, 40 °C)	0.774 (liquid, 70 °C)
	27.5	243.5	0.15 (solid)	0.814 (solid, 20 °C)
1-Tetradecanol	38	205	0.358 (solid, 25 °C)	
Paraffin C ₁₆ –C ₂₈	42–44	189	0.21 (solid)	0.765 (liquid, 70 °C)
				0.910 (solid, 20 °C)
Paraffin C ₂₀ –C ₃₃	48–50	189	0.21 (solid)	0.769 (liquid, 70 °C)
				0.912 (solid, 20 °C)
Paraffin C ₂₂ –C ₄₅	58–60	189	0.21 (solid)	0.795 (liquid, 70 °C)
				0.920 (solid, 20 °C)
Paraffin wax	64	173.6	0.167 (liquid, 63.5 °C)	790 (liquid, 65 °C)
		266	0.346 (solid, 33.6 °C)	916 (solid, 24 °C)
			0.339 (solid, 45.7 °C)	
Polyglycol E6000	66	190.0	n.a.	1085 (liquid, 70 °C)
				1212 (solid, 25 °C)
Paraffin C ₂₁ –C ₅₀	66–68	189	0.21 (solid)	0.830 (liquid, 70 °C)
				0.930 (solid, 20 °C)
Biphenyl	71	119.2	n.a.	991 (liquid, 73 °C)
				1166 (solid, 24 °C)
Propionamide	79	168.2	n.a.	n.a.
Naphthalene	80	147.7	0.132 (liquid, 83.8 °C)	976 (liquid, 84 °C)
			0.341 (solid, 49.9 °C)	1145 (solid, 20 °C)
			0.310 (solid, 66.6 °C)	
Erythritol	118.0	339.8	0.326 (liquid, 140 °C)	1300 (liquid, 140 °C)
			0.733 (solid, 20 °C)	1480 (solid, 20 °C)
HDPE	100–150	200	n.a.	n.a.
Trans-1,4-polybutadiene (TPB)	145	144	n.a.	n.a.

Appendix 3 - Inorganic substances with potential use as PCMs

Compound	Melting temperature (°C)	Heat of fusion (kJ/kg)	Thermal conductivity (W/m K)	Density (kg/m ³)
H ₂ O	0	333	0.612 (liquid, 20 °C)	998 (liquid, 20 °C)
		334	0.61 (30 °C)	996 (30 °C)
				917 (solid, 0°C)
LiClO ₃ ·3H ₂ O	8.1	253	n.a.	1720
ZnCl ₂ ·3H ₂ O	10	n.a.	n.a.	n.a.
K ₂ HPO ₄ ·6H ₂ O	13	n.a.	n.a.	n.a.
NaOH·3 $\frac{1}{2}$ H ₂ O	15	n.a.	n.a.	n.a.
	15.4			
Na ₂ CrO ₄ ·10H ₂ O	18	n.a.	n.a.	n.a.
KF · 4H ₂ O	18.5	231	n.a.	1447 (liquid, 20 °C)
				1455 (solid, 18 °C)
				1480
Mn(NO ₃) ₂ ·6H ₂ O	25.8	125.9	n.a.	1738 (liquid, 20 °C)
				1728 (liquid, 40 °C)
				1795 (solid, 5 °C)
CaCl ₂ ·6H ₂ O	29	190.8	0.540 (liquid, 38.7 °C)	1562 (liquid, 32 °C)
	29.2	171	0.561 (liquid, 61.2 °C)	1496 (liquid)
	29.6	174.4	1.088 (solid, 23 °C)	1802 (solid, 24 °C)
	29.7	192		1710 (solid, 25 °C)
	30			1634
	29–39			1620
LiNO ₃ ·3H ₂ O	30	296	n.a.	n.a.
Na ₂ SO ₄ ·10H ₂ O	32.4	254	0.544	1485 (solid)
	32	251.1		1458
	31–32			
Na ₂ CO ₃ ·10H ₂ O	32–36	246.5	n.a.	1442
	33	247		
CaBr ₂ ·6H ₂ O	34	115.5	n.a.	1956 (liquid, 35 °C)
				2194 (solid, 24 °C)
Na ₂ HPO ₄ ·12H ₂ O	35.5	265	n.a.	1522
	36	280		
	35	281		
	35.2			
Zn(NO ₃) ₂ ·6H ₂ O	36	146.9	0.464 (liquid, 39.9 °C)	1828 (liquid, 36 °C)
	36.4	147	0.469 (liquid, 61.2 °C)	1937 (solid, 24 °C)
				2065 (solid, 14 °C)
KF · 2H ₂ O	41.4	n.a.	n.a.	n.a.
K(CH ₃ COO)·H ₂ O	42	n.a.	n.a.	n.a.
K ₃ PO ₄ ·7H ₂ O	45	n.a.	n.a.	n.a.
Zn(NO ₃) ₂ ·4H ₂ O	45.5	n.a.	n.a.	n.a.

Thermal energy storage in Scotland

Compound	Melting temperature (°C)	Heat of fusion (kJ/kg)	Thermal conductivity (W/m K)	Density (kg/m ³)
Ca(NO ₃) ₂ ·4H ₂ O	42.7	n.a.	n.a.	n.a.
	47			
Na ₂ HPO ₄ ·7H ₂ O	48	n.a.	n.a.	n.a.
Na ₂ S ₂ O ₃ ·5H ₂ O	48	201	n.a.	1600 (solid)
	48–49	209.3		1666
		187		
Zn(NO ₃) ₂ ·2H ₂ O	54	n.a.	n.a.	n.a.
NaOH·H ₂ O	58.0	n.a.	n.a.	n.a.
Na(CH ₃ COO) · 3H ₂ O	58	264	n.a.	1450
	58.4	226		
Cd(NO ₃) ₂ ·4H ₂ O	59.5	n.a.	n.a.	n.a.
Fe(NO ₃) ₂ ·6H ₂ O	60	n.a.	n.a.	n.a.
NaOH	64.3	227.6	n.a.	1690
Na ₂ B ₄ O ₇ ·10H ₂ O	68.1	n.a.	n.a.	n.a.
Na ₃ PO ₄ ·12H ₂ O	69	n.a.	n.a.	n.a.
Na ₂ P ₂ O ₇ ·10H ₂ O	70	184		n.a.
Ba(OH) ₂ ·8H ₂ O	78	265.7	0.653 (liquid, 85.7 °C)	1937 (liquid, 84 °C)
		267	0.678 (liquid, 98.2 °C)	2070 (solid, 24 °C)
		280	1.255 (solid, 23 °C)	2180 (solid)
AlK(SO ₄) ₂ ·12H ₂ O	80	n.a.	n.a.	n.a.
KaI(SO ₄) ₂ ·12H ₂ O	85.8	n.a.	n.a.	n.a.
Al ₂ (SO ₄) ₃ ·18H ₂ O	88	n.a.	n.a.	n.a.
Al(NO ₃) ₃ ·8H ₂ O	89	n.a.	n.a.	n.a.
Mg(NO ₃) ₂ ·6H ₂ O	89	162.8	0.490 (liquid, 95 °C)	1550 (liquid, 94 °C)
	90	149.5	0.502 (liquid, 110 °C)	1636 (solid, 25 °C)
			0.611 (solid, 37 °C)	1640
			0.669 (solid, 55.6 °C)	
(NH ₄)Al(SO ₄) · 6H ₂ O	95	269	n.a.	n.a.
Na ₂ S·5· $\frac{1}{2}$ H ₂ O	97.5	n.a.	n.a.	n.a.
CaBr ₂ ·4H ₂ O	110	n.a.	n.a.	n.a.
Al ₂ (SO ₄) ₃ ·16H ₂ O	112	n.a.	n.a.	n.a.
MgCl ₂ ·6H ₂ O	117	168.6	0.570 (liquid, 120 °C)	1450 (liquid, 120 °C)
	115	165	0.598 (liquid, 140 °C)	1442 (liquid, 78 °C)
	116		0.694 (solid, 90 °C)	1569 (solid, 20 °C)
			0.704 (solid, 110 °C)	1570 (solid, 20 °C)
Mg(NO ₃) · 2H ₂ O	130	n.a.	n.a.	n.a.
NaNO ₃	307	172	0.5	2260
	308	174		2257
		199		
KNO ₃	333	266	0.5	2.110
	336	116		
KOH	380	149.7	0.5	2.044

Thermal energy storage in Scotland

Compound	Melting temperature (°C)	Heat of fusion (kJ/kg)	Thermal conductivity (W/m K)	Density (kg/m ³)
MgCl ₂	714	452	n.a.	2140
NaCl	800	492	5	2160
	802	466.7		
Na ₂ CO ₃	854	275.7	2	2.533
KF	857	452	n.a.	2370
K ₂ CO ₃	897	235.8	2	2.290

Appendix 4 - Metals with potential use as PCMs

Metal	Melting point (°C)	Boiling point (°C)	Latent heat (kJ/kg)	Density (kg/m ³)	Specific heat capacity (kJ/kg·°C)	Thermal conductivity (W/m·°C)
Hg	-38.87	356.65	11.4 ^(a)	13546 ^(a)	0.139 ^(a)	8.34 ^(a)
Cs	28.65	2023.84	16.4 ^(d)	1796 ^(d)	0.236 ^(d)	17.4 ^(d)
Ga	29.80	2204.8	80.12 ⁽ⁿ⁾	5907 ⁽ⁿ⁾	0.37 ⁽ⁿ⁾	29.4 ⁽ⁿ⁾
Rb	38.85	685.73	25.74	1470 ^(m)	0.363 ^(m)	29.3 ^(m)
K	63.20	756.5	59.59 ^(d)	664 ^(m)	0.78 ^(m)	54.0 ^(m)
Na	97.83	881.4	113.23 ^(d)	926.9 ^(d)	1.38 ^(d)	86.9 ^(d)
In	156.80	2023.8	28.59 ^(m)	7030 ^(c)	0.23	36.4 ^(c)
Li	186.00	1342.3	433.78	515	4.389	41.3
Sn	231.9	2622.8	60.5 ^(m)	730 ^(d)	0.221	15.08 ^(b)
Bi	271.2	1560	53.3	979	0.122	8.1

(a) 25°C ; (b) 200°C ; (c) 150°C ; (m)100°C ; (n) melting temperature

Appendix 5 - Alloys with potential use as PCMs

Number	Melting point (°C)	Composition				
		Bi	Pb	Sn	Cd	Other
1	46.8	44.7	22.6	8.3	5.3	In 19.1
2	58.0	49.0	18.0	12.0	—	In 21.0
3	60.0	53.5	17.0	19.0	—	In 10.5
4	70.0	50.0	18.7	23.3	10.0	—
5	72.0	34.0	—	—	—	In 66.0
6	78.8	—	57.5	17.3	—	In 25.2
7	91.5	51.6	40.2	—	8.2	—
8	95.0	52.5	32.0	15.5	—	—
9	102.5	54.0	26.0	—	20.0	—
10	124.0	55.5	44.5	—	—	—
11	130.0	56.0	—	40.0	—	In 4.0
12	138.5	58.0	—	42.0	—	—
13	142.0	—	30.6	51.2	18.2	—
14	144.0	60.0	—	—	40.0	—
15	177.0	—	—	67.75	32.25	—
16	183.0	—	38.14	61.86	—	—
13	199.0	—	—	91.0	—	Zn 9.0
14	221.0	—	—	96.5	—	Ag 3.5
15	236.0	—	79.9	—	17.7	Sb 2.6
16	247.0	—	87.0	—	—	Sb 13.0
17	70.0-72.0					
18	70.0-78.9	50.5	27.8	12.4	9.3	-
19	70.0-83.9	50.0	34.5	9.3	6.2	-
20	70.0-90.0	50.72	30.91	14.97	3.4	-
21	70.0-101.1	42.5	37.7	11.3	8.5	-
22	95.0-103.9	35.1	36.4	19.06	9.44	-
23	95.0-148.9	56.0	22.0	22.0	-	-
24	95.0-148.9	67.0	16.0	17.0	-	-
25	95.0-142.8	33.3	33.33	33.3	-	-
26	102.6-226.7	48.0	28.5	14.5	-	Sb 9.0
27	138.3-170.0	40.0	-	60.0	-	-

Appendix 6 - Current large scale (>100kW) cold storage projects

Project Name	Location	Technology Type	Description	Rated Power (kW)	Duration (h)
The State of North Carolina	North Carolina, USA	Chilled Water Thermal Storage	2.68 million gallon, chilled water	2,590	8
University of Central Florida	Florida, USA	Chilled Water Thermal Storage	Chilled water storage integrated into the existing district cooling system	3,000	8
Cache Creek Casino	California, USA	Chilled Water Thermal Storage	To shift 900 KW of electric load from the peak electric period to the off-peak period.	1,300	6
VA Medical Center	Texas, USA	Chilled Water Thermal Storage		2,300	8
Lackland Air Force Base	Texas, USA	Chilled Water Thermal Storage	A 792,000 gallon storage tank rated at 6600 ton-hours of TES	580	8
Geisinger Health System	Pennsylvania, USA	Chilled Water Thermal Storage	The storage tank is rated at 8000 ton-hrs.	700	8
University of Texas Pan-Am	Texas, USA	Chilled Water Thermal Storage	A1.07 MG, 10,000 ton-hr storage tank.	875	8
Texas Instruments Manufacturing Plant	Texas, USA	Chilled Water Thermal Storage	A first tank of 2.7 MG, 24,500 ton-hr and a second tank of 5.2 MG, 48,730 ton-hrs.	6,400	8
Federal Government Facility Chilled Water TES	Virginia, USA	Chilled Water Thermal Storage	0.11 MG	274	2.5
American Online Data Center	Virginia, USA	Chilled Water Thermal Storage	Rated at 4,350 ton-hours.	1,500	2
Thermal Storage at San Antonio International Airport	Texas, USA	Chilled Water Thermal Storage	A maximum rate of 4,500 ton-hours.	422	8
Disney California Adventure	California, USA	Chilled Water Thermal Storage	A 12,000 ton-hr tank.	2,000	4
UCI Microgrid: Thermal Storage	California, USA	Chilled Water Thermal Storage	A 4.5 million gallon chilled water tank to service an average cooling load of 74,400 ton-hours per day.	6,590	8
Redding Electric Utilities - Peak Capacity, Demand Response, HVAC Replacement Program	California, USA	Ice Thermal Storage	1MW of Ice Bear; the system costs \$2170/kW.	1,000	6
Ice Energy Anaheim Energy Storage Project	California, USA	Ice Thermal Storage		200	5

Thermal energy storage in Scotland

Glendale Water and Power - Peak Capacity Project	California, USA	Ice Thermal Storage	A total of 180 Ice Bear units have been installed; the system costs \$2170/kW.	1,500	6
Southern California Edison - HVAC Optimization Program with energy storage	California, USA	Ice Thermal Storage	Costs \$1800/kW for businesses installation.	750	6
St. Kilian Parish and School	Pennsylvania, USA	Ice Thermal Storage		100	6
Bethel Park High School	Pennsylvania, USA	Ice Thermal Storage	A 432 tons tank was installed and 2250 net usable tn hours of storage resulting in an average demand reduction of 375 kW.	375	6
Duquesne University	Pennsylvania, USA	Ice Thermal Storage	A 6000 tn-hours system was installed.	600	6
University of Arizona	Arizona, USA	Ice Thermal Storage	205 tanks in total.	3,000	6
EPCC Thermal Storage: Valle Verde	Texas, USA	Ice Thermal Storage	The campus is completely cooled by ice storage during peak demand, saving more than \$145,000 dollars per year.	930	8
El Capitan	California, USA	Ice Thermal Storage	A 25 percent reduction in annual energy costs, saving approximately \$23,000 in utility costs each year.	150	6
Mission City Office Complex	California, USA	Ice Thermal Storage		500	7
Fossil Ridge High School	Colorado, USA	Ice Thermal Storage		200	8
O-I World Headquarters	Ohio, USA	Ice Thermal Storage	A 400 ton peak cooling load.	250	12:0.00
Redding Electric Utilities - Peak Capacity, Demand Response, HVAC Replacement Program Phase 2	California, USA	Ice Thermal Storage	Can reduce peak electricity load demand by up to 6 MW.	6,000	2
Nissan Technical Center North America Inc	Michigan, USA	Ice Thermal Storage		1,425	16
JC Penney Headquarters	Texas, USA	Ice Thermal Storage	One of the largest thermal energy storage systems in the world;	4,425	12
Fort Collins Utilities Four Cities Smart Grid Development Project- New Belgium Brewery Site	Colorado, USA	Ice Thermal Storage	Can achieve a 20-30 percent peak load reduction.	135	6
Park Marina Building	California,	Ice Thermal		132	6

Thermal energy storage in Scotland

	USA	Storage			
Nordstrom, Inc	Hawaii, USA	Ice Thermal Storage	Produce 43 tons of ice every night.	1,200	6
CALMAC Centex Building	Texas, USA	Ice Thermal Storage	14 Ice Bank tanks.	205	6
Shell Point Retirement Village	Florida, USA	Ice Thermal Storage		4,800	6
CLPCCD - Utility Infrastructure Project	California, USA	Ice Thermal Storage		890	5
ConEdison Interoperability of Demand Response Resources: Thermal	New York, USA	Ice Thermal Storage	10,000 cooling tons of ice.	1,000	10
SCPPA Thermal Energy Storage Program	California, USA	Ice Thermal Storage	Approximately 2.5MW is installed.	2,427	6
1500 Walnut	Pennsylvania, USA	Ice Thermal Storage		210	6
Ice Energy project at 1894 Churn Creek Rd	California, USA	Ice Thermal Storage		120	6
Ice Energy project at 2680 Radio Ln	California, USA	Ice Thermal Storage		170	6
EPCC Thermal Storage: Rio Grande	Texas, USA	Ice Thermal Storage	Has 12 thermal storage units.	180	8
EPCC Thermal Storage: Transmountain	Texas, USA	Ice Thermal Storage	Has 15 units.	225	8
Sarasota County School District	Florida, USA	Ice Thermal Storage	Achieved over \$2 million in annual energy cost savings.	20,000	8
GridSolar Boothbay Pilot Project: Thermal Storage (Peak Shaving)	Maine, USA	Ice Thermal Storage	29 Ice Bear units.	221	8
Ice Energy project at 901 E Alosta Ave	California, USA	Ice Thermal Storage		120	6
Ice Energy project at 701 E. Foothill Blvd	California, USA	Ice Thermal Storage		120	6
Ice Energy project at 35960 Rancho California	California, USA	Ice Thermal Storage		210	6