Final report: ADSorB Advancing Distributed Storage for grid Benefit

Net Zero Innovation Portfolio: Longer Duration Energy Storage (Phase 2)

September 2025

Contents

Abbreviations

Abbreviation	Meaning
API	Application programming interface
ASHP	Air source heat pump
BRE	Building Research Establishment
CAPEX	Capital expenditure
CPD	Continuing Professional Development
DHW	Domestic hot water
DSR	Demand side response
EV	Electric vehicle
HP	Heat pump
HWT	Hot water tank
MPC	Model predictive control
OPEX	Operation (and maintenance) expenditure
PCM	Phase change material
PSSR	Pressure Systems Safety Regulations 2000
PV	Photovoltaic
RTE	Round trip efficiency
SAP	Standard Assessment Procedure
SH	Space heating
SOC	State of Charge
TCS	Thermochemical Storage
TOUT	Time of use tariff
TRL	Technology readiness level

Project summary

This report summarises the outcomes from the Advancing Distributed Storage for grid Benefit (ADSorB) project, funded by the Department for Energy Security and Net Zero (DESNZ) through the Net Zero Innovation Portfolio (NZIP) Longer Duration Energy Storage (LoDES) competition. The project was a collaboration between the University of Sheffield (UoS, project lead), the Centre for Renewable Energy Systems Technology (CREST) at Loughborough University, the University of Nottingham (UoN) and Mixergy Ltd.

The LoDES competition was motivated by the contribution that longer duration energy storage (defined in the competition guidance as being greater than four hours, but potentially spanning days, weeks, or months) could make to reducing the cost of meeting Net Zero targets by storing excess low carbon generation for longer periods of time, helping to manage variation in generation such as extended periods of low wind. The ability to do so could reduce the amount of fossil fuel and low carbon generation that would otherwise be needed and optimise the output from renewables.

Addressing this challenge will require the development and deployment of a broad range of storage technologies covering a full spectrum of scales, locations, capacities, response times and storage durations. The ADSorB project focused on the development and real-world demonstration of two innovative longer duration thermal storage technologies initially developed at CREST. The thermochemical storage (TCS) and phase change material (PCM) technologies considered are designed to operate as part of an intelligent, modular domestic energy system alongside other low-carbon technologies. Both technologies offer energy storage at far greater densities than traditional hot water stores; both use materials with minimal environmental impact; and both offer storage at extended durations - up to inter-seasonal in the TCS case.

If delivered at scale, these technologies present huge opportunities for aggregation of distributed energy resources to significantly enhance UK energy flexibility. Installing the PCM systems demonstrated within the project, into one million of the UK's ~30M homes could provide up to 13.5GWh of thermal storage alone, with the developed TCS unit potentially offering even greater capacity. By way of comparison, the UK's largest pumped hydropower plant (Dinorwig) has a capacity of 9.1GWh of electrical energy which must subsequently be dispatched via the grid.

Storing this heat at the point of use is a major benefit of distributed systems, avoiding grid constraints during periods of peak electrical demand. This will become increasingly important as heat and transport electrify, adding burden to the already challenged energy networks. Additionally, the ability to shift substantial quantities of hot water and space heating demand from peak to off-peak periods has the potential to deliver significant benefits to end users making use of time of use tariffs (TOUTs). One finding of the project is that this could be sufficient to bring the cost of providing heating via an air source heat pump (ASHP) to substantially below the cost of doing so using a gas boiler using currently available tariffs.

Project Scope

The ADSorB project was conducted over two phases. Phase 1 of the project ran from February to Jun 2022 and enabled the technical and commercial feasibility of the thermal storage technologies to be established. At the conclusion of Phase 1, a full-scale PCM system had been characterised in a laboratory environment, with the technical performance of a reduced-scale prototype TCS system having also been established. The two technologies were considered to have achieved a technology readiness level (TRL) of 4-5. The PCM store was demonstrated to offer performance in excess of existing commercial offerings, with the TCS store being truly novel, with no product based on this technology having yet made its way to market and presenting the opportunity to capture and store energy for weeks or even months.

The aim of Phase 2 of the project, covered by this report, was to progress both technologies to TRL 7 (demonstration in an operational environment). The project objectives were:

- Manufacture and characterise PCM and TCS storage devices at the CREST lab.
- Develop control hardware and software to operate the devices.
- Install the storage and control systems at five trial sites of varying types.
- Monitor and evaluate performance within the operational test site environments.
- Iteratively update the systems and controllers in response to project learnings.
- Understand the benefits of the technologies to end users and broader energy system.
- Carry out a detailed performance characterisation of the stores in controlled laboratory environments at both single unit and systems-level.
- Assess the commercial case for the developed technologies.

Trials methodology

Three trials were hosted at the Creative Energy Homes (CEH) campus at the University of Nottingham's Department of Architecture and Built Environment where existing properties provide a testbed for novel building technologies. Equipment was installed into two occupied residential units and the district heat network (DHN). These enabled TRL 7 *demonstration of an actual system prototype in an operational environment*. Two test environments at the University of Sheffield - the Laboratory for Verification and Validation (LVV) and the Low Carbon Laboratory (LCL) - supported and expanded upon activities at CEH.

1930s semi-detached house

This building represents a redevelopment of a typical 1930s semi-detached house such that it would comply with zero-carbon targets. From the 1930s to 1960s there was a large house build programme in the UK. These houses currently make up around 60% of the UK housing stock; retrofitting homes from this era to increase their overall energy efficiency represents a major opportunity to reduce UK carbon emissions. The adjoining property is simulated using a narrow ancillary structure, which is used to locate monitoring equipment. As part of the project the existing gas boiler was replaced with an Air Source Heat Pump (ASHP) and the prototype PCM storage which served both space heating (SH) and domestic hot water (DHW) demand. The system was housed in the ancillary structure shown in Figure 1, enabling access without impacting residents. In a real-life scenario, the storage system would preferably be located inside a house such that the stores benefit from a warmer ambient temperature and to ensure that thermal losses (heat emitted) stays inside the building envelope.

Figure 1: The CEH 1930's house with ancillary structure shown to the left.

Low energy house

This property was built to explore passive house principles, having highly insulated north, east and west walls with minimal openings and fully glazed sun space to the southern elevation.

Figure 2: CEH Low energy house.

As part of the project an existing low temperature ASHP was replaced with a unit capable of providing the higher flow temperatures needed to charge the PCM stores. The PCM system was installed in the plant space at the front of the house. The TCS system was installed into a new external store shown in Figure 3. The house had an existing solar thermal hot water system which was incompatible with modern equipment. This was replaced with a new Mixergy solar PV-compatible DHW tank, enabling future PV retrofit.

Figure 3: The Daikin heat pump alongside the shed constructed to house the TCS system.

Low Temperature District Heat Network (DHN)

The CEH campus has a low temperature DHN that enables heat generated by each property to be fed into the communal store. Stored heat can be used by each property for SH and DHW needs. The DHN offers an ideal testbed to demonstrate alternative longer duration energy storage technologies.

CEH properties have a range of heat generators: ASHP, solar thermal and gas boilers, supplemented by electric resistive heating using a solar PV source. A 10,000 litre GALÚ Classic hot water store provides storage. The project assessed the feasibility of using a large scale TCS system with greatly increased storage density (targeting 288kWh of storage within a 2m^3 volume) to replace large water storage tanks in heat networks.

Laboratory for Verification and Validation (LVV)

Figure 4: Environmental chambers at the Laboratory for Verification and Validation (LVV).

To fully characterise the physical behaviour of the modules and develop advanced methods for state of charge (SoC) estimation, a programme of unit-level testing in controlled environmental conditions was conducted at the LVV at the University of Sheffield.

The environmental chambers (Figure 4) enabled the performance of the individual TCS and PCM modules to be evaluated across a broad range of operating conditions. Charging and discharging of the system was conducted using an experimental rig built around a Huber 510 thermoregulated source. The experimental programme at the LVV comprised:

- Experimental testing of modules and systems in controlled environments.
- Development of advanced state estimation techniques based upon measured data.
- Support for the iterative cost- and performance-optimisation of the storage modules.

Low Carbon Laboratory (LCL) at the University of Sheffield

A new laboratory-based system was built at the LCL to allow the novel thermal energy storage devices to be tested at domestic scale, including interactions with heating technologies. The system (Figure 5) acted as a “physical twin” of the systems installed at CEH. It enabled development of the design, operation and control of the prototype storage devices to be tested at system level before testing within homes. The rig also offers the possibility of extension to alternative heat sources and storage devices, enabling testing of scenarios that are not possible within occupied trial homes.

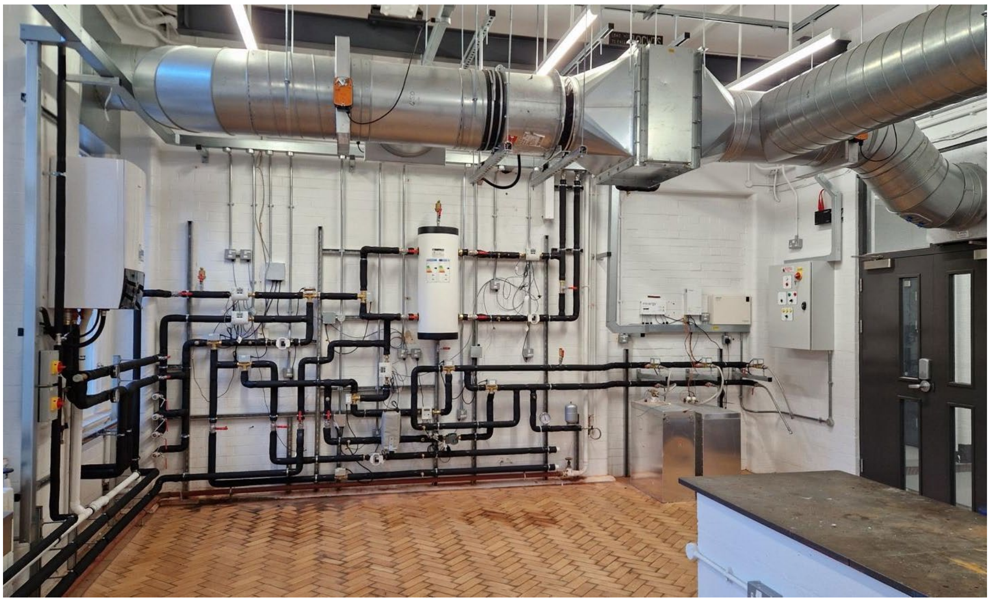

Figure 5: The Low Carbon Laboratory (LCL) at the University of Sheffield.

The system operation was controlled by a bespoke IoT-connected controller developed by Mixergy, enabling both rule-based scheduling and model predictive control. LCL used the same monitoring platform adopted for the CEH installations, enabling extensive electrical, flow rate and temperature metering in order to evaluate the system performance. The hydraulic setup was designed to be highly flexible and allows the thermal storage devices to serve both DHW and SH demands either directly (i.e. completely removing load from the heat pump) or indirectly by preheating the return flow to the heat pump.

Phase change material (PCM) thermal

The aim of this workstream was to bring the PCM stores to TRL7 ("successful demonstration of the devices in an operational environment") from an initial TRL of 4/5. This represents a key step towards commercialisation that can identify areas for improvement and optimisation ahead of manufacture at scale. Key objectives are summarised below:

- Manufacture and initial characterisation of four sets of full-scale Gen 2 PCM systems at CREST, with each system comprising three storage units. The storage capacity of each three-module system was expected to exceed 10kWh across a 37°C to 57°C temperature range. The Gen 2 stores are based on a Gen 1 design developed and manufactured during Phase 1 of the ADSorB project.
- Install the storage and control systems at four trial sites: CEH houses, LVV and LCL.
- Monitor and evaluate performance and make iterative improvements in the operational environments at CEH.
- Detailed characterisation of first and second generation stores in controlled conditions at the LVV, enabling quantification of store-level round-trip-efficiencies (RTEs) across a set of standing periods, alongside building a detailed understanding of charge and discharge behaviour at differing states of charge.
- System-level testing at the LCL, enabling characterisation of system performance across a broader operational envelope than may be achieved in the occupied homes at CEH, and enabling development and optimisation of control approaches ahead of on-site deployment.

Centre for Renewable Energy Systems Technology (CREST)

The work done at CREST to develop PCM heat storage for domestic applications included:

- Adapting an existing modular PCM store design to increase energy storage capacity.
- Reducing heat losses from the stores to enable longer storage periods.
- Manufacturing modules for the test sites.
- Experimentally characterising unit performance.
- Development of a future PCM design in response to lessons learned across the project.

Technical outputs

Manufacture and characterisation testing

Building on the previous store designs, the module design was modified to increase the quantity of phase change material from 40 to 45 kg and the energy storage capacity by approximately 12.5%. This increase was based on the design of the heat exchanger and led to an increase in the thermal storage capacity (latent and sensible) of the PCM from 2.85 to 3.20kWh in the temperature range from 37°C to 57°C. Over the same temperature range the sensible heat capacity of the heat exchanger, module inner walls and heat transfer fluid is approximately 0.24kWh. The theoretical total heat storage capacity in the temperature range from 37°C to 57°C for the improved module design was 3.44kWh.

Charging and discharging the store over a greater working temperature range provides rapid and efficient charging during and above the phase change temperature, greater effective thermal storage capacity and higher initial output powers. This can be achieved by using an input charge temperature of 70°C from a high temperature heat pump and an input discharge cold water temperature (mains) of 10°C with a resulting potential operating temperature range of 10°C to 70°C.

The 10°C to 70°C temperature range increases the energy storage capacity of each module with the increased PCM mass from approximately 4.19 to 4.55kWh. The capacities of the three-module thermal storage system being 10.32kWh in the temperature range from 37°C to 57°C and 13.65kWh in the range from 10°C to 70°C.

Thicker insulation was used to reduce standby heat losses; for example, if the store is charged at night between 10pm and 5am when grid electrical loads are low and later discharged between 5pm and 8pm when grid loads are high. Foam insulation was used in the prototype. Higher performance insulation could be used to create more compact units.

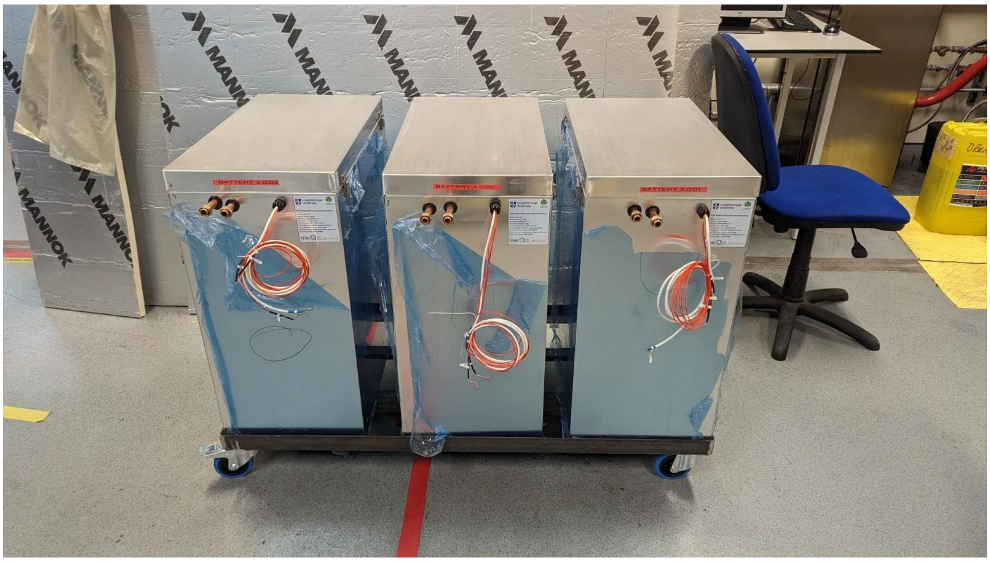

Figure 6: Three second-generation PCM modules on a trolley.

Figure 7: A three module PCM store under test at CREST thermal store test facility.

Performance of the PCM stores is presented in Figure 8, Figure 9 and Figure 10 which clearly show the potential to deliver high rates of power for short periods of time or low rates of power for longer periods at temperatures above 50°C. The store was initially charged to 70°C and subsequently discharged to inlet water at 10°C to simulate domestic hot water provision or providing heat to a cold central heating system.

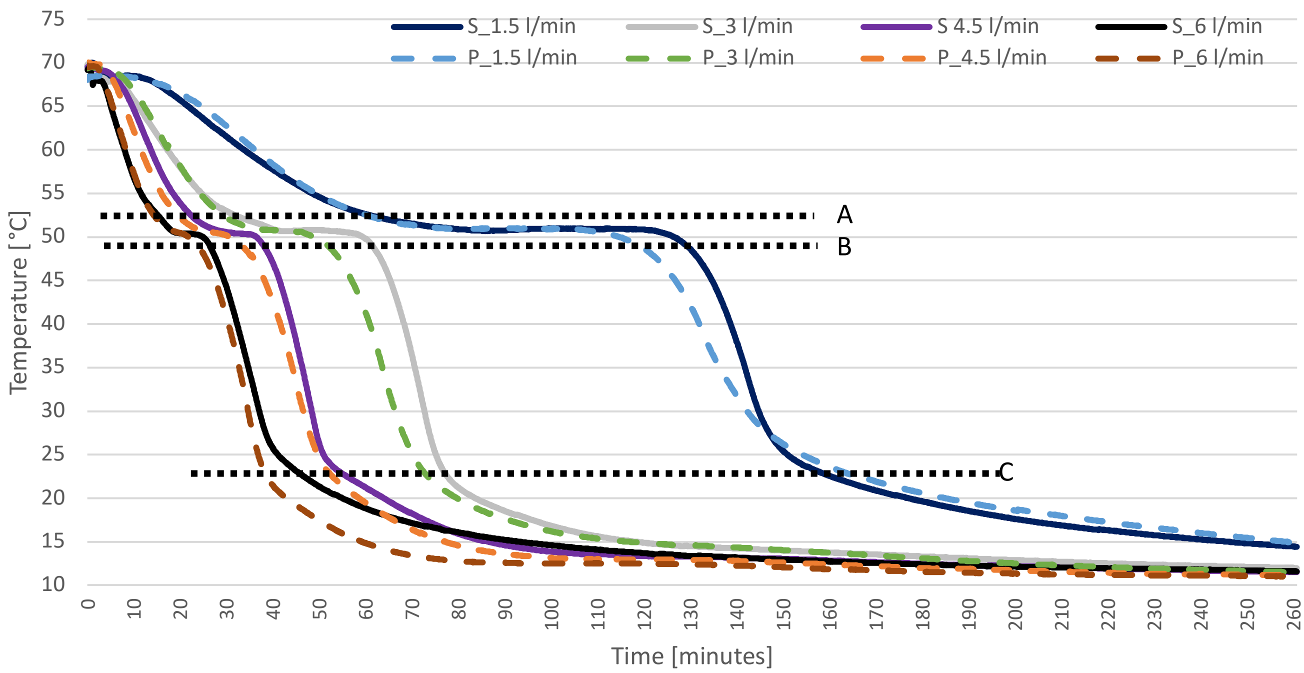

Figure 8: Measured outlet temperatures for modular PCM store with parallel (P) and series (S) flow arrangement.

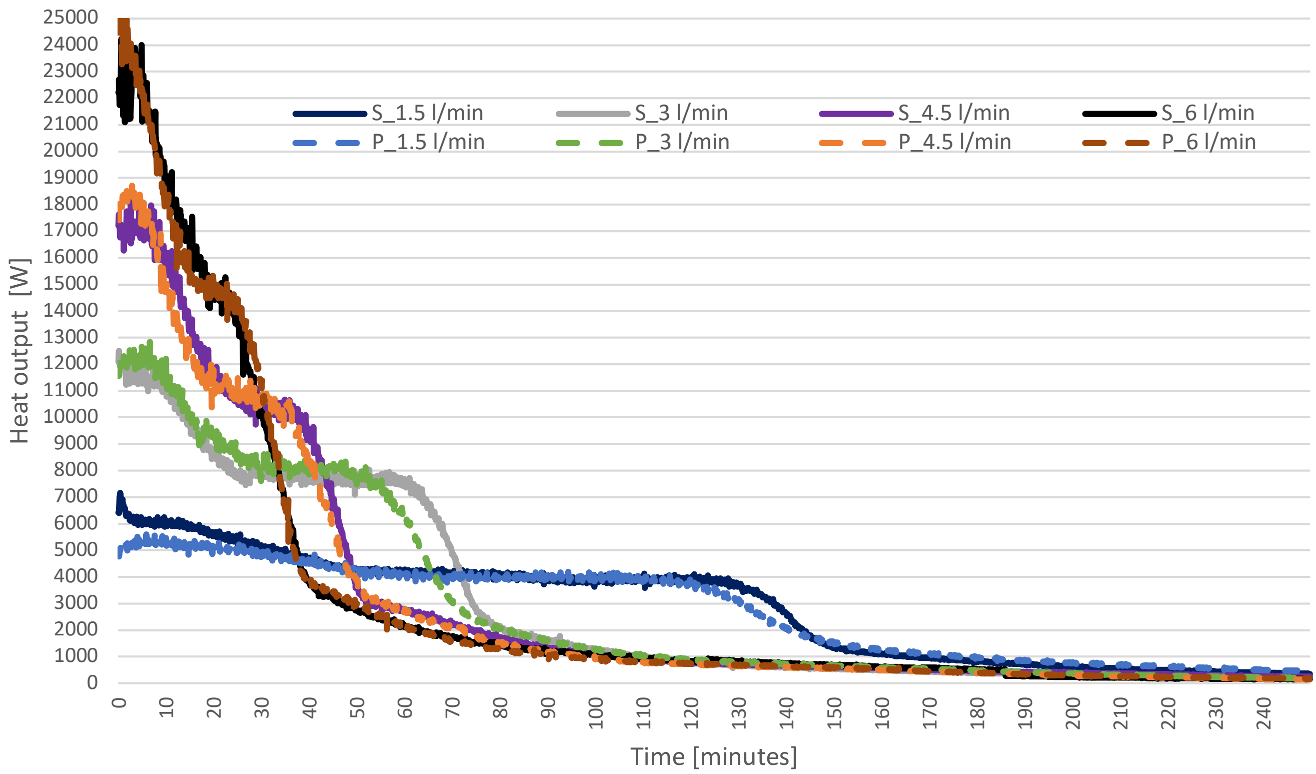

Figure 9: Power output rates calculated based on heat transfer fluid mass flow and measured temperature difference between the store inlet and outlet for parallel (P) and series (S) flow arrangements.

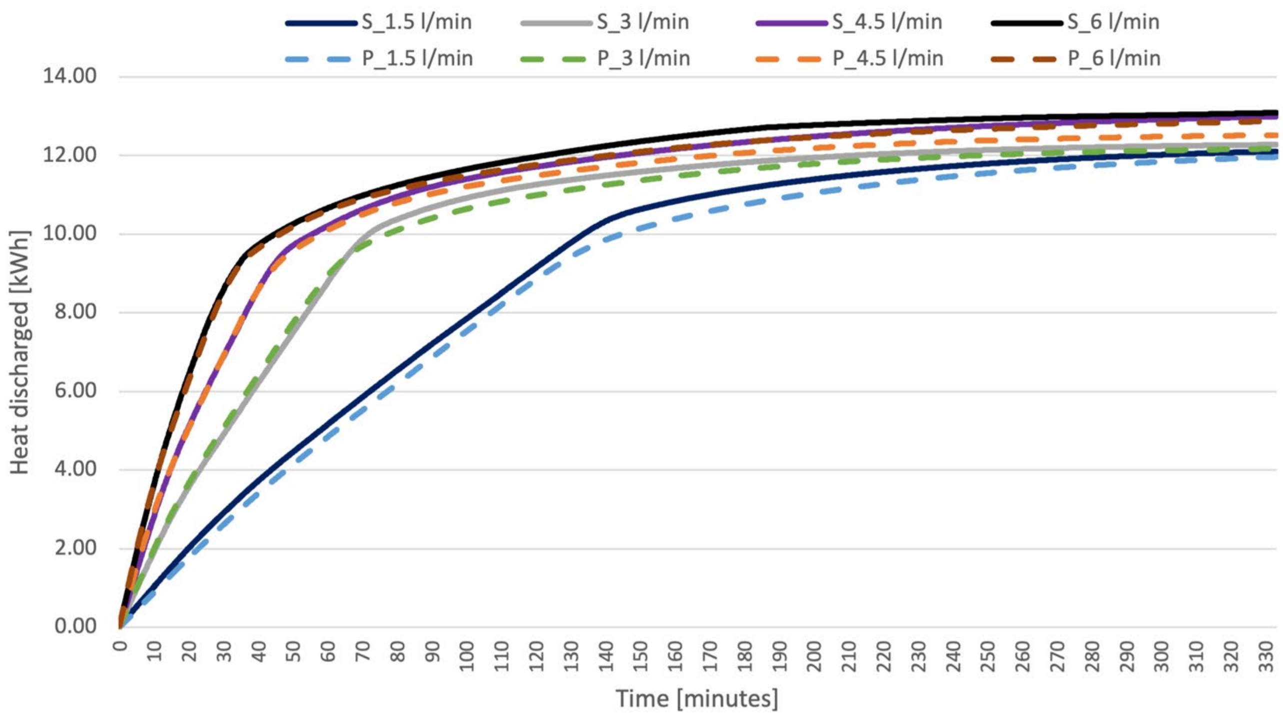

Figure 10:The calculated cumulative heat delivered from the PCM store for series (S) and parallel (P) flow arrangements.

Summary of characterisation test outcomes

The main outcomes of the work are that:

- A PCM store using a 53°C bio-based phase change material, CrodaTherm 53, was designed to be charged with high temperature domestic heat pumps (T_{charge} = 70°C).
- Modules and stores were fabricated and characterised at CREST prior to dispatch.
- Design modifications increased phase change storage capacity by 12.5% and reduced heat losses by 50% allowing longer times between charging and discharging.

When the store is charged to 70°C the results of lab experiments are shown in Figure 11, Figure 12 and Figure 13. It can be seen that:

- The heat output rates for parallel and series flow arrangements generally follow similar profiles; however, the series flow arrangement maintains a constant power output during phase change for slightly longer than the parallel flow arrangement.
- At the start of the discharging process due to the large temperature difference between the cold heat transfer fluid at 10°C and the store, high heat output rates result, over 24kW for 6 l/min, 18kW for 4.5 l/min, 12kW for 3 l/min and 5.5 to 6kW for 1.5 l/min, a near linear relationship of heat output with flow volume.
- When the PCM phase change commences, the rate of decrease in heat output reduces, with a period of more stable heat output achieved. As the temperature of the liquid PCM in the store decreases, the rate of heat output decreases. After the phase change period, the rate of heat output decreases slowly approaching zero.
- For the different flow rates 6, 4.5, 3 and 1.5 l/min the average values of heat output during phase change are 15, 10.5, 8 and 4kW for approximate durations of 10, 20, 40 and 80 minutes corresponding to 2.5, 3.5, 5.3 and 5.3kWh.
- For each of the flow rates, over 10kWh of heat is delivered at temperatures above 50°C.

The lab performance indicates that the 3-unit PCM store design, if charged to 70°C, can provide over 10kWh of heat at different power rates depending on inlet flow velocity and inlet temperature to meet subsequent demands within a 24 to 48 hour period.

Issues identified with the developed PCM thermal stores and proposed solutions.

Issues identified during the development of the Gen 2 PCM stores were:

- Pressure loss through the store heat exchanger.
- Weight of stores for transport and installation.

Pressure loss: To address the pressure loss through the store's single heat exchanger, a modified design was proposed. The updated design employs three smaller heat exchangers connected by a manifold at each end. The combination of reduced fluid flow velocities through each mini-heat exchanger and the shorter flow path length would be expected to lead to an overall 27-fold reduction in heat exchanger pressure losses.

An added advantage of the approach of using smaller size modular heat exchangers in parallel is that a wider range of store configurations becomes possible. Individual storage units can be sized in multiples of 1.43 or 2.38kWh enabling thermal stores to be sized for different building space heat loads and smaller stores to be developed for distributed hot water loads for example, showers. This is in addition to the option of having multiple storage units to provide distributed storage if advantageous. Having single larger stores for a given storage requirement reduces the quantity of insulation required for a specified level of heat loss and reduces the total volume of the store.

The internal PCM store enclosure would be sized to have internal dimensions based on the new two pipe row mini heat exchangers of:

- L_{int} = 505mm
- H_{int}= 420mm x 1.2 = 504mm
- W_{int}= 90mm x n

with n being the number of heat exchanger units included in each store. The factor of 1.2 multiplier applied to the height allows for expansion of the PCM and the parallel flow manifold. The outer enclosure would be sized to allow for the required thickness of insulation based on thermal conductivity and intended time between charge and discharge, i.e. if 30mm of insulation is sufficient the outer enclosure internal store dimensions would become:

- L_{out} = 505mm + 2mm + 60mm = 567mm
- H_{out}= 504mm + 2mm + 60mm = 566mm
- W_{out}= 90mm x n + 2mm + 60mm

The 2mm allows for a wall thickness of the internal container of 1mm. For a store comprised of six mini heat exchangers in parallel (i.e. with W_{int} = 540mm), the store would have a thermal storage capacity of 8.58 kWh and a surface area, SA, of 1.599m^2 according to,

- $SA = 2 \times (L_{int} \times H_{int} + L_{int} \times W_{int} + W_{int} \times H_{int})$ = 1.599m^2

A 30mm thickness, Δx, of insulation with a thermal conductivity k of 0.03 Wm^{-2}K^{-1} would give a heat loss rate, HL, from a store heated to 70°C to an ambient environment at 20°C (i.e. a temperature difference ΔT=50°C) of 79.9W or 0.0799kWh per hour according to,

- $HL = k/\Delta x \times SA \times \Delta T$ = 0.03/0.03 ×1.599 × (70-20) = 79.9W

Based on the heat storage capacity of 8.58kWh, this indicates a maximum heat loss rate of approximately 1% per hour. This calculation does not include the effects of thermal contact resistance and thermal surface resistance which would reduce heat losses further.

Weight of stores for transport and installation

To reduce the weight of the store and improve the ease of store installation and transport, the store can be transported empty with the phase change material (PCM) introduced into the store when it is in place. The proposed method to do this is by having packages of PCM that are of the correct weight for the heat exchange elements, these would be transported to site and melted on site prior to being introduced into the store. Melting would require a bespoke temperature-controlled heating system, similar to a large scale electric domestic kettle with temperature control and a detachable pouring mechanism. To avoid potential issues with PCM solidification blocking the store inlet port, the pouring mechanism used would enable the liquid PCM to be introduced at different heights within the store commencing from the base of the store. Additional liquid layers of PCM would be added while increasing the height of the pouring mechanism until the required weight of PCM is introduced to the store. At end of life the store would either be heated and the liquid PCM decanted for recycling, or the unit could be removed from the installation site and emptied at a recycling facility.

Additional options to reduce the store size other than using the mini heat exchanger modules while maintaining the energy storage capacity essentially require either i), the level of insulation to be reduced or ii), that the insulation is replaced by an insulation with a lower thermal conductivity allowing a thinner layer to be used. When a system is to be charged and discharged within a day period, the preferred option would be charged and discharged twice in a day, then the current level of insulation in the Gen 3 PCM stores can be reduced, reducing the store volume. When the system is charged and discharged after a period of two to three days then the use of vacuum insulation panels with their lower thermal conductivity, would be an option to reduce the store size while maintaining current low levels of heat loss although insulation costs will increase.

Temperatures required for PCM store charging

To achieve effective melting of the PCM and heat delivery to the store during charging it is important that the heat delivery temperature is a minimum of 10°C greater than the phase change temperature, temperatures less than this will result in decreased heat transfer rates and concomitant increased charging times. The temperature recommended for the PCM used, CrodaTherm 53 is an inlet temperature of 70°C. The mass flow rate $\dot{m}$ required through the heat exchanger is dependent on the outlet temperature from the store T_{out} and the available rate of power input Q. With C_p being the specific heat capacity of water, the required mass flow rate may be calculated as,

$$\dot{m} = Q/C_p(70 - T_{out})$$

When discharging, if volume flows through the heat exchanger are high then the rise in temperature through the store will be reduced. It is important that flow rates are selected to enable the required delivery temperatures to be achieved. For the three-module store developed and tested, flow rates of 1.5 to 6 l/min can deliver temperatures over 50°C with an inlet temperature of 10°C for periods from 30 to 130 minutes with power outputs from 4 to over 15kW. Figure 8 to Figure 10 provide experimentally measured data of discharging performance for the developed three-module PCM store system with different heat transfer fluid flow rates.

Economic considerations

When the 10kWh of heat to charge the store is supplied by a high temperature heat pump with a seasonal coefficient of performance (COP) of 2.5, the equivalent input of electricity will be approximately 4kWh. Modelled costs for a number of scenarios are illustrated in Table 1 .

Table 1: Illustration of breakeven point for a 10 kWh PCM thermal store.

Store Capital Cost (£)	1000	1000	2000	1000	2000	2000
Store Capacity (kWh)	10	10	10	10	10	10
Annual Cycles	120	120	120	80	80	80
Annual interest rate	0.05	0.05	0.05	0.05	0.05	0.05
Tariff difference (£/kWh)	0.2	0.2	0.2	0.2	0.4	0.4
Tariff inflation rate	0.05	0.05	0.05	0.05	0.05	0.05
Heat Pump COP	2.5	2.5	2.5	2.5	2.5	3
Annual maintenance (£)	0	50	0	0	0	0
Breakeven Year	11	17	21	16	16	19

Assumptions:

- Capital cost of mass-produced 10kWh PCM heat store would be £1,000 to £2,000.
- Modelled on one cycle per day, with heating seasons of 120 or 80 days.
- Purchase of system would be funded by a loan, with an annual loan interest rate and tariff inflation rate of 5%.
- Running cost savings would result from difference between electricity tariffs between store charge and discharge stages.
- Typical seasonal COP for ASHP in the UK is around 2.8 (~3); COP 2.5 was used in model as ASHPs with higher operating flow temperatures have a lower COP.
- Negligible maintenance cost would be required in addition to the annual ASHP maintenance/inspection.

Outcomes

- Manufacture of a set of PCM storage units for installation at the test sites.
- Modification of the initial design to:
  - Enable a 12% increase in active material volume, improving storage capacity.
  - Greatly reduce the rate of heat loss through the walls of the unit with insulation.
- Initial characterisation to establish storage capacities and charge/discharge profiles for a range of flow rates.
- Proposal of modifications to the heat exchanger to reduce pressure losses.

Creative Energy Homes (CEH)

Work undertaken at CEH aimed to build a detailed understanding of the PCM stores and controls performance when operated in a realistic environment. An extended testing period during the 2024/25 winter heating season identified a range of operational challenges that were investigated and addressed. The challenges included installer experience, heat pump interoperability and control software development. A substantial number of charge and discharge cycles to both space heating and domestic hot water demonstrated that the PCM systems could be operated successfully within the homes.

Changes to the system design during the project focused on the hydraulic connection between the primary circuit and the PCM stores. Figure 11 shows the final schematic.

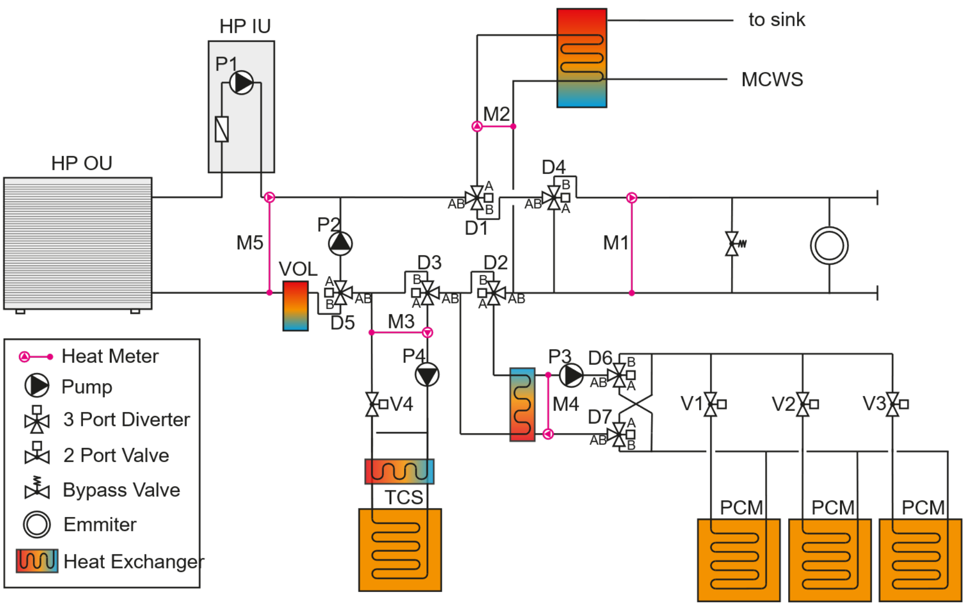

Figure 11: Schematic representation of the systems installed at CEH homes.

Technical outputs

Heat pump and PCM installation

The ASHP installed into the homes was capable of producing up to 65ºC without the need for the built-in auxiliary heater. The selected ASHP is ideal for retrofit situations that require higher flow temperatures to enable re-use of existing radiators and pipework, and provided output temperatures appropriate to the PCM stores.

Space constraints presented a challenge when accommodating the prototype 3-unit PCM stores within the properties. For the 1930s property, space was found in an ancillary structure adjoining the house. For the low energy house, the PCMs were accommodated within the existing plant room.

Figure 12: PCM thermal stores installed into the 1930s house.

Figure 13: PCM stores installed in the low energy house.

PCM operation: Initial trials

The integrated PCM store and ASHP system was designed to use off-peak electricity periods during charging. Figure 14 presents outcomes from an initial trial based upon the Octopus 'Cosy' tariff. In this test, the controller was programmed to charge the PCM stores during an off peak period, and then immediately discharge them into the DHW cylinder during the following standard/peak period. While this is useful to demonstrate successful system and controller function, for the majority of the tests presented in this section the focus was on shifting of space heating loads, rather than DHW. In this configuration, the controller was setup to initially meet SH loads using the charged PCM stores, and then switch to using the heat pump directly once the stores were exhausted. One key observation from these initial trials was that the ASHP's integrated pump was not powerful enough to overcome pressure losses across the PCM stores; a further pump was added to the system to overcome this issue.

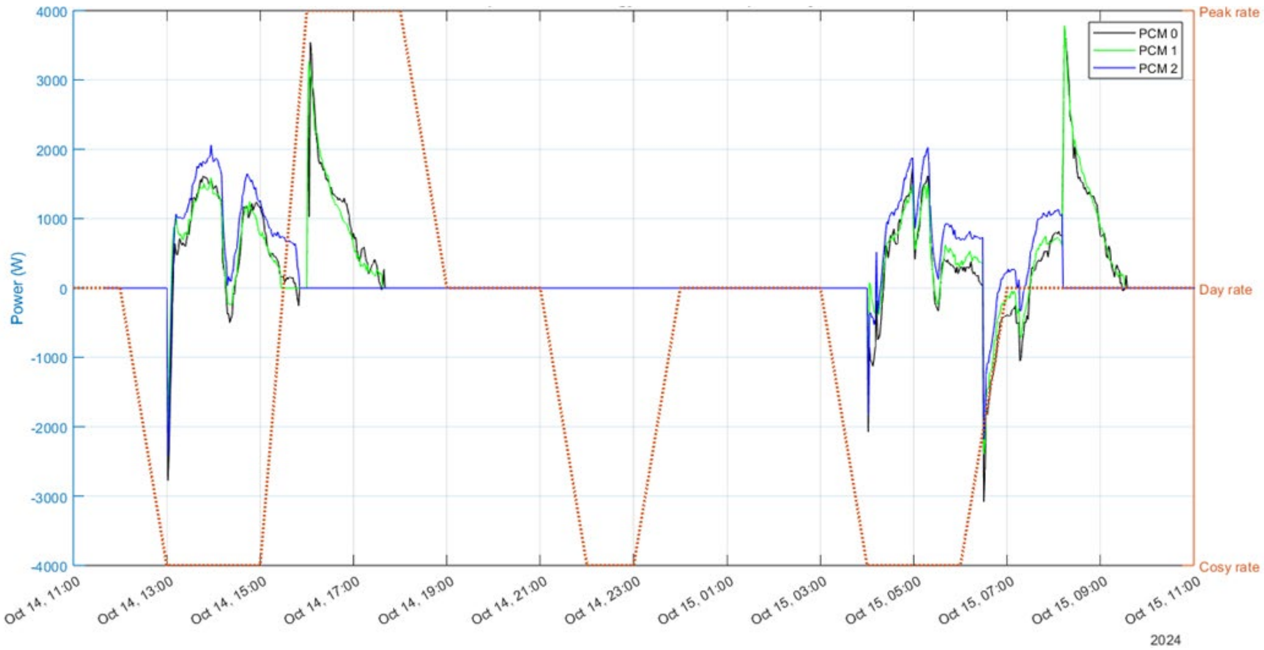

Figure 14: ASHP charging the PCM stores at tariff off-peak points, followed by discharge.

The following figures provide a detailed illustration of the PCM store performance within the test houses. Figure 15 shows the PCM material temperatures in one of the three stores, illustrating the storage temperature profile during daily charging and discharging cycles. A sustained charging temperature above 53ºC is required to melt the PCM material. It was established that a totally cold store sitting at around room temperature may require two off-peak charging periods to reach the melting point. When the PCM stores were cycled regularly, and thus charging was started from a higher initial internal temperature, they reached the melting point in a single charging cycle. This supports the hypothesis that operating the stores in a comparatively narrow range around the phase change temperature will offer benefits over using a broader range, and highlights the importance of developing appropriate SoC estimation methods to support optimised control of the stores.

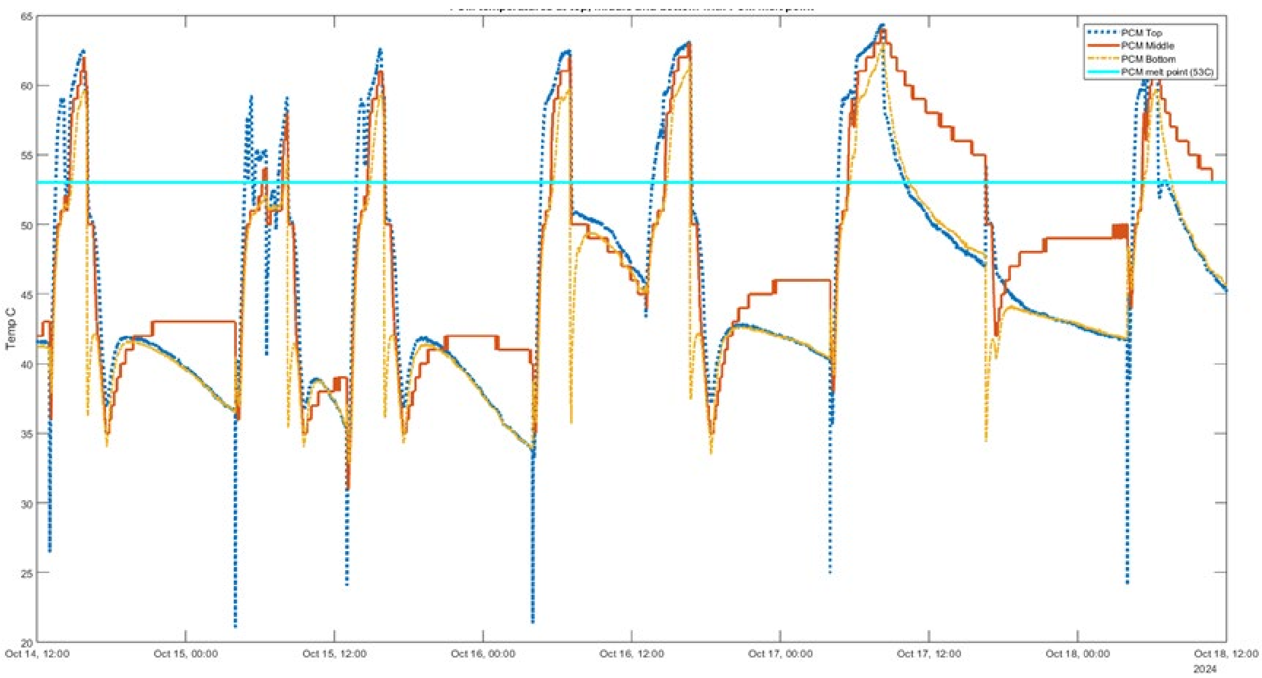

Figure 15: Temperature at top, middle and bottom of one of PCM units within the 1930s house, with PCM melting point shown in light blue.

Figure 16 shows the daily cycle over 36 hours. The stores were limited to one charge/discharge for each Cosy period. This made best use of the cheapest tariff price point and maximised the opportunity to discharge.

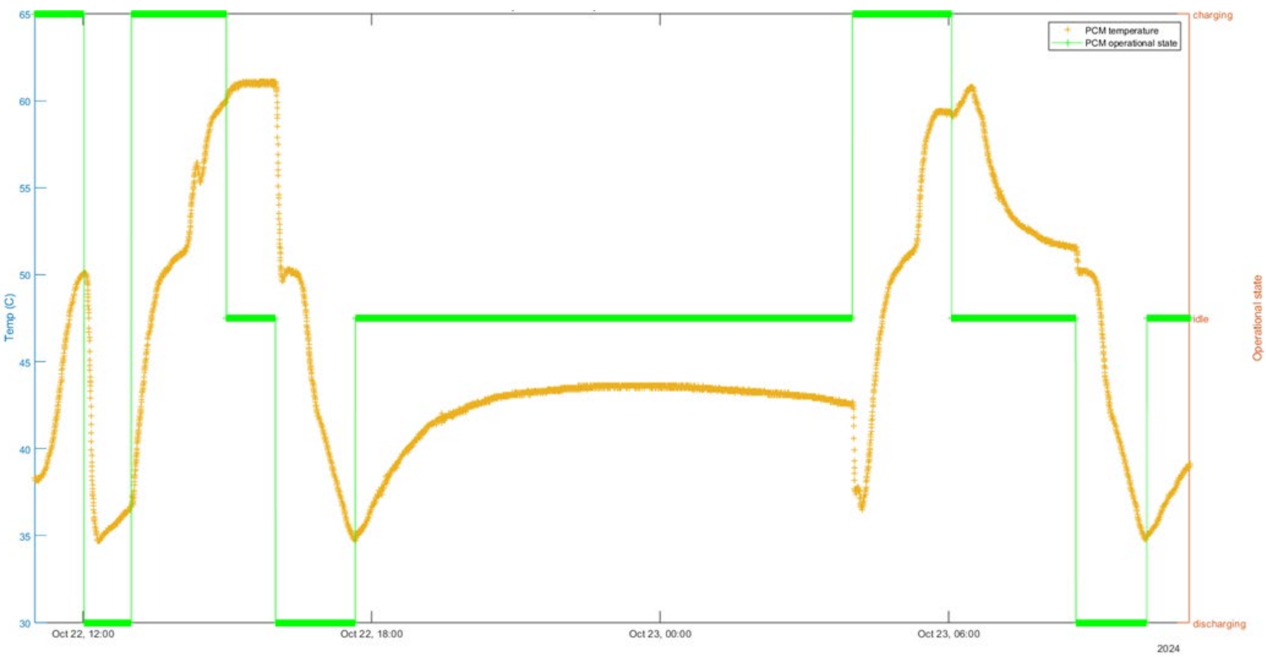

Figure 16: PCM temperature and operational states over 36 hours in October 2024.

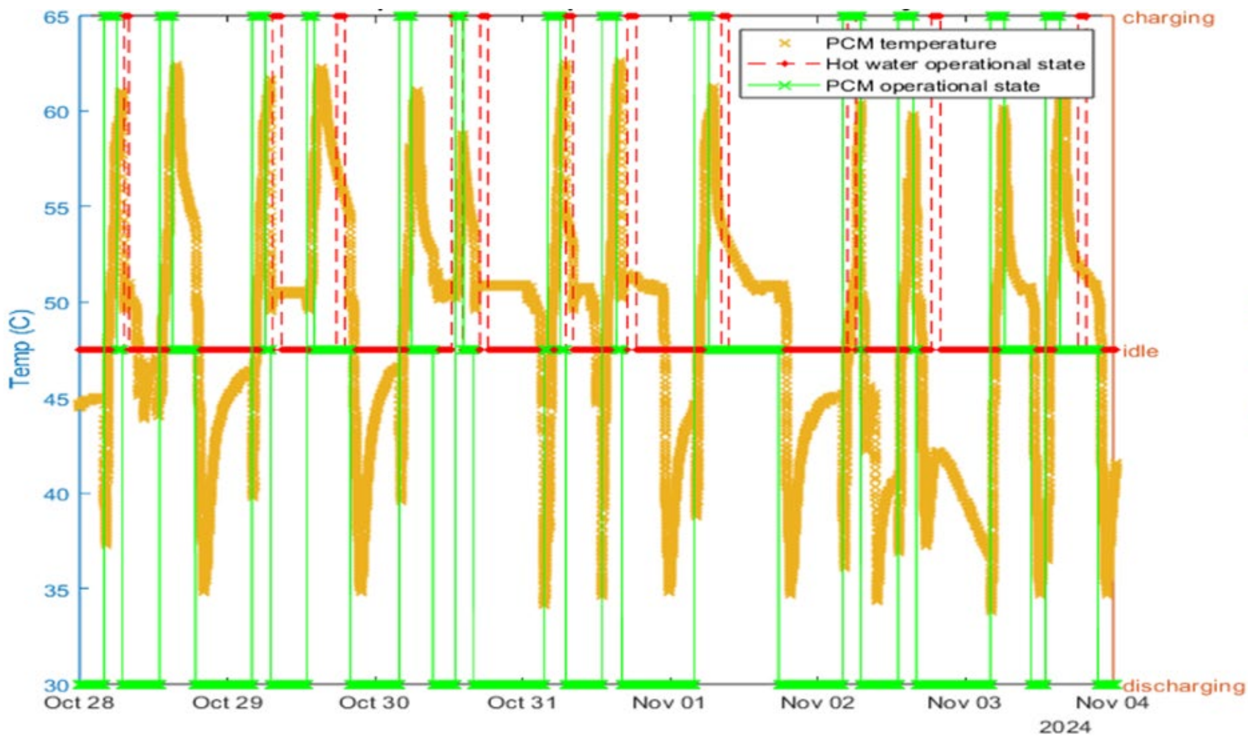

Figure 17: PCM temperature and operational state over seven days in October/November 2024. Discharge was to the DHW cylinder.

Figure 17 extends Figure 16, showing a seven-day operation period with a complete charge and discharge cycle once a day. The ASHP fully charges the PCM store and continues to provide heat into the DHW system. This scheduling pattern allows the DHW to benefit from the large amount of heat already flowing within the primary circuit of the heating system.

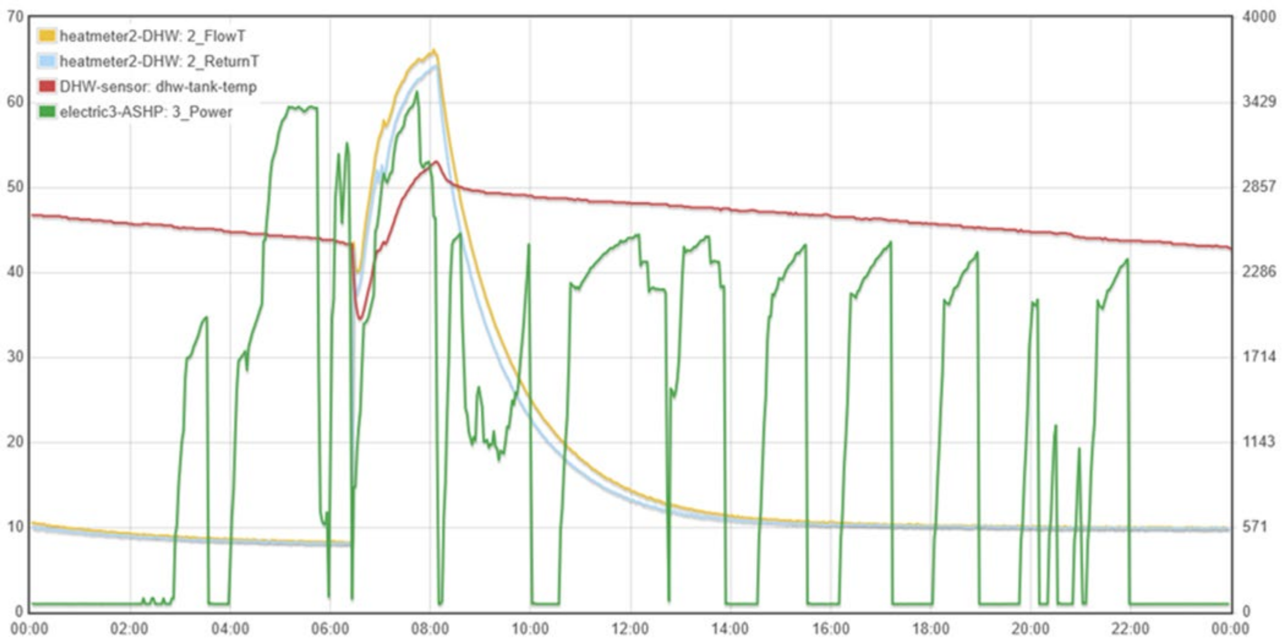

Figure 18: DHW cylinder temperature, DHW heat meter flow and return temperatures and ASHP electricity consumption on one day in January 2025. Temperature ºC on left axis and watts on right axis.

Figure 18 overlays ASHP power consumption on DHW heat meter flow and return temperatures. The DHW tank temperature is shown to highlight the work done by the heat pump in lifting the tank to the higher temperature setpoint each morning. The PCM stores are able to complete their charging cycle before the end of the 7am Cosy period. In this case some of the heat pump's power consumption is at the discounted Cosy rate. However, it takes until 8:08am before the DHW cylinder reaches the higher setpoint. Most of this work is accomplished in the standard rate period, receiving no discount per kWh consumed. The tank does not receive additional charging most of the day, only being charged a second time if there is significant draw of hot water by the home.

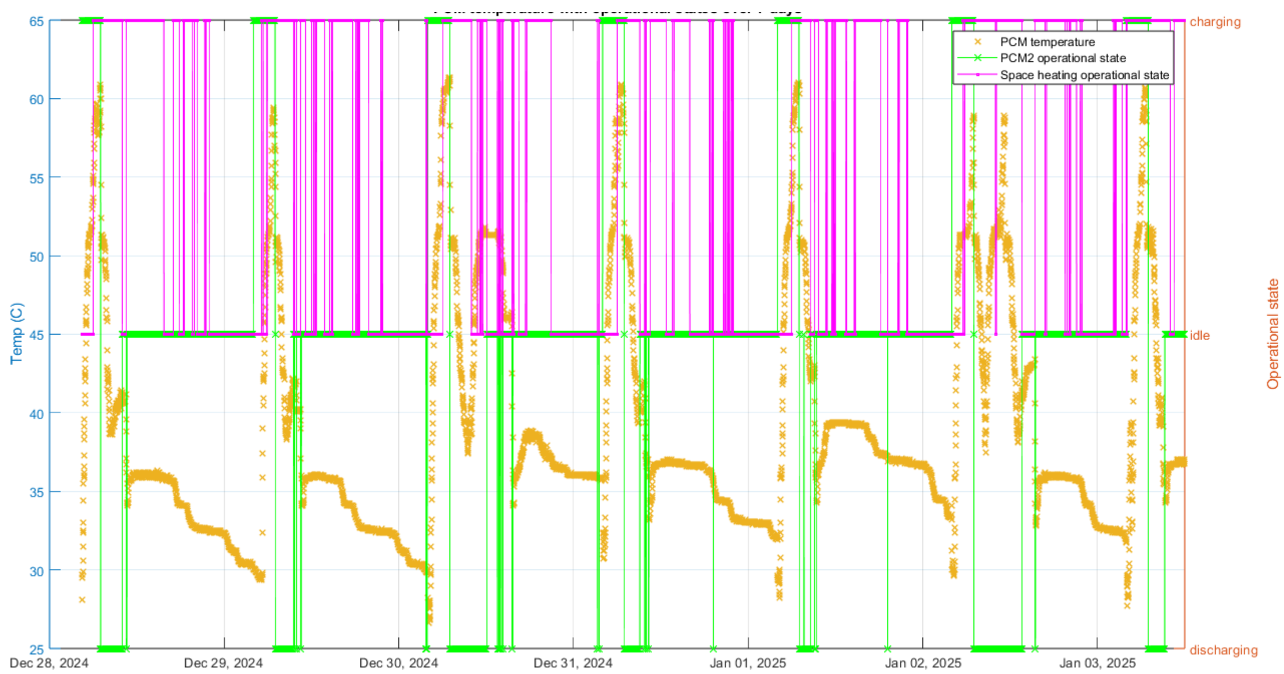

Figure 19: PCM temperature and operational state over seven days, with PCM stores providing space heating.

Figure 19 contains the seven-day operational state of the PCM stores discharging to space heating. As temperatures within the house change, the sensor may direct the controls to shut off the store due to the lower temperature threshold having been reached. After sitting idle for a short time, the temperatures within the store may change and the store is now able to meet the criteria for discharge. The controls open a valve and allow the store to discharge energy into the main heating circuit. This on/off behaviour was observed frequently with the stores installed at Nottingham.

In Figure 20 the effect of PCM discharge into the space heating circuit, following charging in the morning 4am to 7am Cosy period, is observed. The temperature increase is in response to the 4.5kW power output of the combined stores. Temperature tops out at 65°C briefly and fluctuates throughout the whole discharge period. There is a long section where temperatures in the PCM stores and the temperature in the space heating circuit are stable. The heat pump's output temperature for space heating is 50ºC. The figure shows the heat pump is doing the majority of the work after a certain point, but the PCM stores may still be open to exchange energy with the system due to the lower temperature threshold not being met for shutting down.

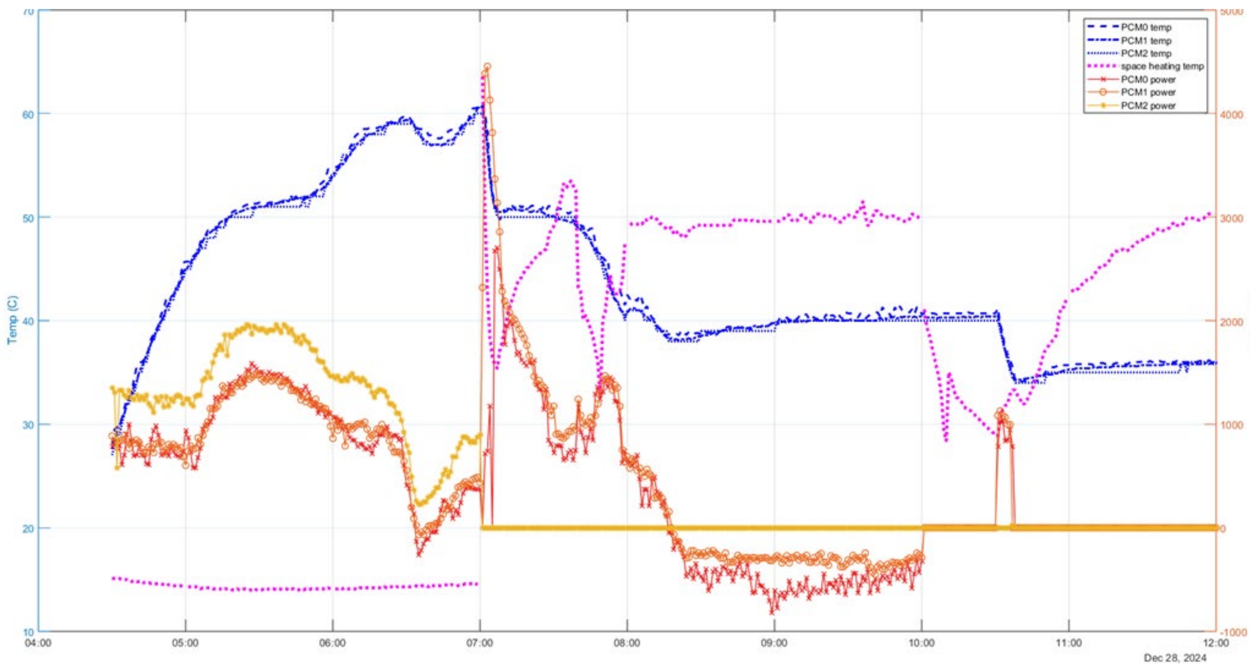

Figure 20: Effect of PCM discharge on space heating temperatures during a morning charge/discharge cycle in December 2025.

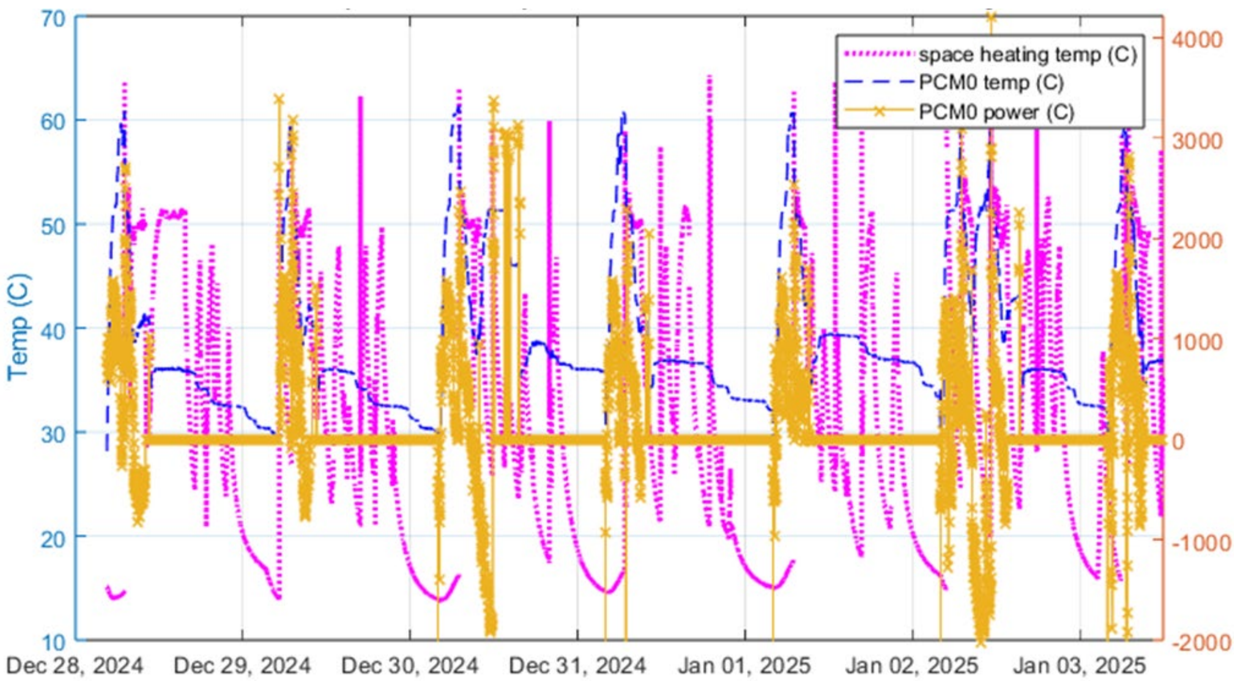

Figure 21: PCM temperature and input/output power over seven days, with PCM stores providing space heating.

Figure 21 gives a longer view of seven days with PCM and heat pump meeting space heating demand. In this example the daily temperatures and powers achieved by the system are consistent.

Addressing operational challenges that occurred during testing

- **Flow rates.** Early trials found that flow rates through the thermal stores were lower than through the ASHP. These irregular flows were detected by the ASHP which then triggered a shutdown. To allow different flow rates to exist within the same system, a low-loss header (rated at 50kW) was added. This successfully enabled two separate flows to enter a common chamber where mixing and thermal transfer could take place.
- **Risk of PCM material leaking into heating circuit.** Testing at the LCL found that there was a potential for liquid PCM material to leak into the home heating circuit as it passed through the store. To prevent this at CEH, the PCM store was hydraulically separated from the main heat pump systems to completely remove the risk of contamination to the tenanted property's heating systems. The low-loss header was removed and replaced with a similarly rated plate heat exchanger. A more powerful pump was fitted to the PCM loop to enable higher flow rates through this circuit, benefiting the heat transfer between the heat pump and PCM stores.
- **Moving from DHW to SH provision using PCM stores.** The PCM stores were initially used solely for DHW provision; this testing took place during the summer period, where there was minimal SH demand. The PCM stores were charged during the off-peak Cosy period from 4am to 7am, then immediately discharged into the DHW tank. However, it was noted that the morning usage of hot water was not sufficient to significantly reduce the DHW tank temperature. We found that discharging the PCM could slightly lift the DHW tank temperature, but it did not fully discharge the PCM store's energy. After several hours of discharging the stores, the temperature within the PCM and DHW stores reached equilibrium, preventing any further energy transfer to the DHW tank. When the PCM discharge cycle ended the hot water had not reached the higher setpoint, resulting in the heat pump having to come up to temperature to finish taking the DHW to the required setpoint. Approaching winter, the control code was modified to prioritise use of the PCM stores for space heating, with the heat pump used to provide DHW without support from the PCM stores. The PCM stores were again charged during the morning Cosy tariff period (4am to 7am). If space heating demand existed at the end of this off-peak period, the stores were set to discharge into the SH circuit. This operation mode utilised the energy in the PCM stores to a greater extent, resulting in greater depth of discharge. Once the PCM stores were discharged, the system reverted to using the heat pump to meet SH loads.
- **Freezing temperatures during winter.** A further complication was experienced when outside temperature reached close to freezing (0°C). Flow errors in the heat pump became common, occurring each morning, eventually resulting in a critical stop error and no heating or hot water to the home. This was found to be a result of the ASHP attempting to perform an anti-freezing cycle in response to the cold outside temperature. Valve D5 and pump P2 shown in Figure 11 were being energised such that the heat pump was hydraulically isolated from the primary circuit. The lack of a flow path between the heat pump flow and return legs led to the inbuilt pump (P1 in Figure 11) experiencing a dead-head condition when attempting to run the anti-freeze process, triggering shut down of the heat pump. The system was altered so that the PCM stores

discharged via the heat pump, rather than via the short circuit loop served by valve D5 and pump P2. This enabled trials to proceed on the coldest days and allowed investigation of an operation mode of interest; discharging the PCM stores via the heat pump such that the store output may be “topped up” to the required SH or DHW flow temperature. A key finding was that the electrical load drawn by the heat pump in this mode of operation was high (in excess of 1kW) even when minimal additional heat input was being provided by the heat pump. This highlighted the value of further exploring and optimising heat pump and storage interoperability, addressed later in this report.

Outcomes

- Demonstrated deployment of, and monitoring of PCM systems in a real domestic home environment.
- Sustained operation from September 2024 to January 2025 of the PCM systems with occasional interruptions due to faults and operating code changes, with only two interventions, when the PCM system went offline and required support to be brought back into operation, occurring between December and January.
- In the core 61-day testing period (end of November 2024 to mid-January 2025) there were 65 charging events, 116 discharging events and 100 periods within which the PCM system was idle.
- Over the test period a reported utilisation of the PCM system at each operational state - charging, discharging and idle - were found to be 8%, 31% and 61% respectively. This high proportion of idle state time is due to the time-based control setup adopted during the test period, which sought to cycle the PCM system once per day. It should be noted that these values are based upon the controller *target* states; in practice it was observed that the *actual* energy entering and leaving the stores - recorded by the heat meters - did not completely align with these target operational states.
- It was observed that some periods of energy transfer extended beyond the operational state period; for example, the PCM stores entering a (target) discharge state after a period of charging, but was in actuality still being charged for a period due to thermal inertia within the system. A further example was observed to arise when moving from an idle or discharge state into a charging state; in many instances a substantial lag (in the order of 15-30 minutes) was observed between a call-for-heat being made to the heat pump, and the outlet flow temperature from the heat pump reaching the level required for charging the stores. During this period, the store was discharged to some degree, in direct contravention of the target mode. A key learning was that further precision is required in monitoring and accounting for actual energy flows to and from the PCM store system, for example by delaying operation of the secondary circuit serving the stores (i.e. activating Pump P3 in Figure 11) until the primary circuit has reached a target charge/discharge temperature. Alternative system setups that may further simplify the control approaches required are returned to later in this report (see the “Future PCM deployment: active buffer configuration” section).

The overall conclusion was that the PCM technology itself performed as expected following laboratory trials, and that there is scope for substantial further development of control approaches in order to optimise overall system performance.

Laboratory for Verification and Validation (LVV)

The work conducted at the LVV focused on the detailed characterisation of the performance of the PCM stores in controlled environmental conditions. This involved:

- Commissioning a new thermal testing rig based around a Huber 510 thermoregulated supply and associated acquisition equipment.
- Using this rig to conduct a sequence of charge-idle-discharge cycles with idle periods of differing lengths.

The developed test rig is shown in Figure 22, with a PCM store installed ready for testing in Figure 23. This enabled detailed characterisation of both the charging and discharging profiles of the PCM stores, and the development of round-trip efficiency (RTE) curves covering idle times of zero up to 160 hours. The testing was repeated for the two generations of PCM store manufactured at CREST, enabling comparison of performance.

Figure 22: The thermal testing rig at LVV, with the Huber 510 thermoregulated supply unit shown on the left.

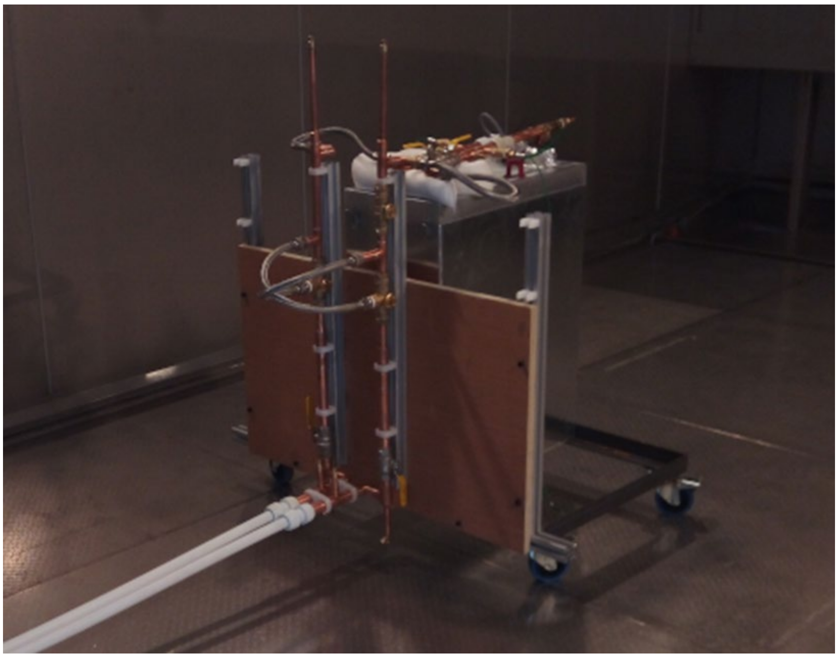

Figure 23: Gen 1 PCM store installed for testing within the LVV environmental chamber.

Technical outputs

The work undertaken allowed for a more detailed understanding to be developed of the operation of the unit. Furthermore, the tests have provided supporting data for the development of the tools described in the State of Charge (SoC) estimation section. The key findings from these tests are round-trip efficiency values for the unit (with values of 85 to 95% achieved for immediate charge-discharge cycles); the maximum length of time that the unit can hold charge; the effect of part-discharge periods; and the length of time that the unit can maintain a steady heat supply in realistic conditions.

Gen 1 Round trip efficiency tests

The key metric on which the performance of the units was evaluated was round trip efficiency (RTE): the ratio between the energy recovered during discharging and the energy supplied during charging of the unit. The RTE represents a combination of the charging efficiency (η_{ch}), discharging efficiency (η_{dch}) and standing losses of the unit and is thus dependent on the standing period between charging and discharging. RTE approaching the product of η_{ch} and η_{dch} (the value of which is not known) would be expected for short standing periods, with RTE reducing for longer standing periods.

Experiments were designed to quantify the RTE over a set of idle periods. Within each test, the unit was fully charged and then disconnected from the heat supply. The unit was then left to stand for a period of time before it was fully discharged. The difference between the energy input into the unit during charging and the energy recovered during the discharge phase was used to calculate the RTE, which could then be estimated as a function of standing period by carrying out multiple experiments over a range of standing periods. The dimensions of the Gen 1 unit and the locations of the thermocouples are shown schematically in Figure 24.

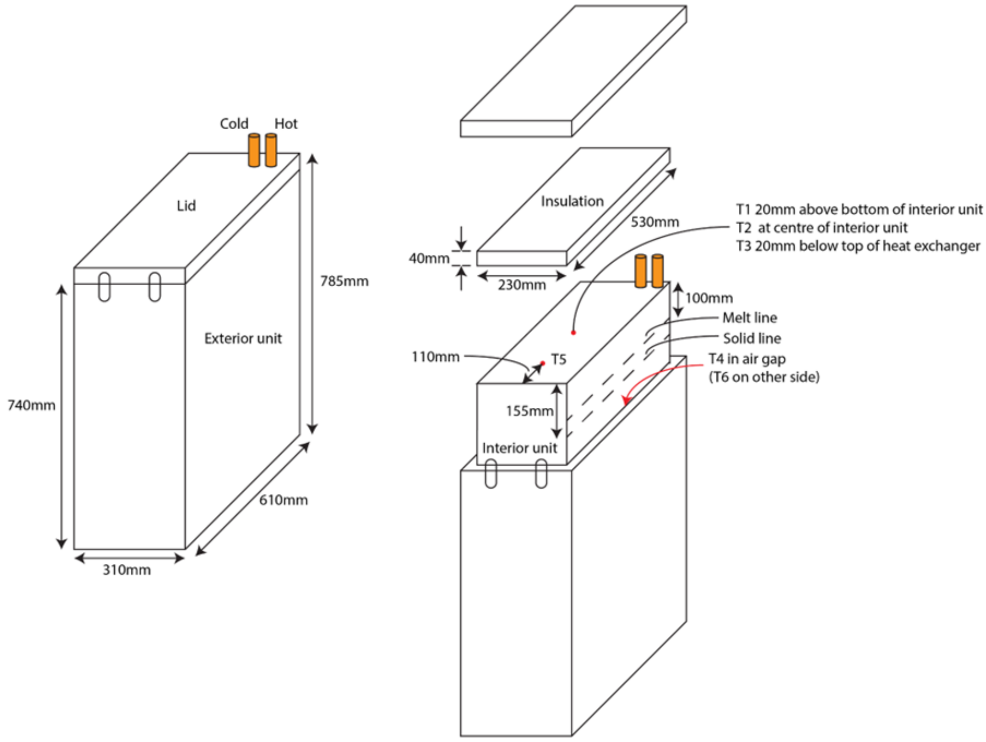

Figure 24: A schematic diagram of the Gen 1 PCM unit indicating dimensions and thermocouple locations.

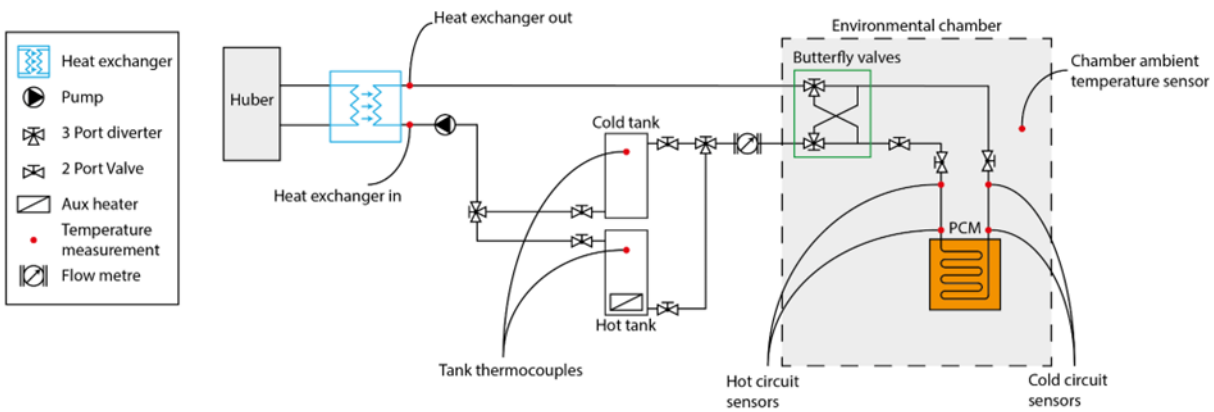

Figure 25: A schematic diagram of the test rig at the LVV including temperature sensor locations.

The recorded data for each test comprised the time stamps, the flow rate through the rig and a series of temperature measurements (the locations of the temperature sensors are indicated in Figure 25).. For all tests described in this section, the unit was charged to 70°C and discharged to 20°C; for these tests, the definition of 'charged' or 'discharged' was based on a qualitative observation that the temperatures recorded at both the internal and outlet sensors had converged to a steady state around the charge or discharge temperature. The ambient temperature was not controlled during these tests but was recorded; and observed to remain within a range of 3°C. Different standing periods were introduced between the charge and discharge periods for each test; these ranged from immediate discharge to a standing period of 160 hours.

The recorded temperatures and flow rates allowed for the charging and discharging power to be calculated for each test. This then enabled both the energy input into the unit during charging, and the energy recovered from the unit during discharging, to be estimated. The difference between the recovered and input energy was used to estimate the combined losses in the system for a given period, comprising the aggregated charging, discharging and standing losses. The quotient between the input and recovered energy values gave an estimate of the round-trip efficiency.

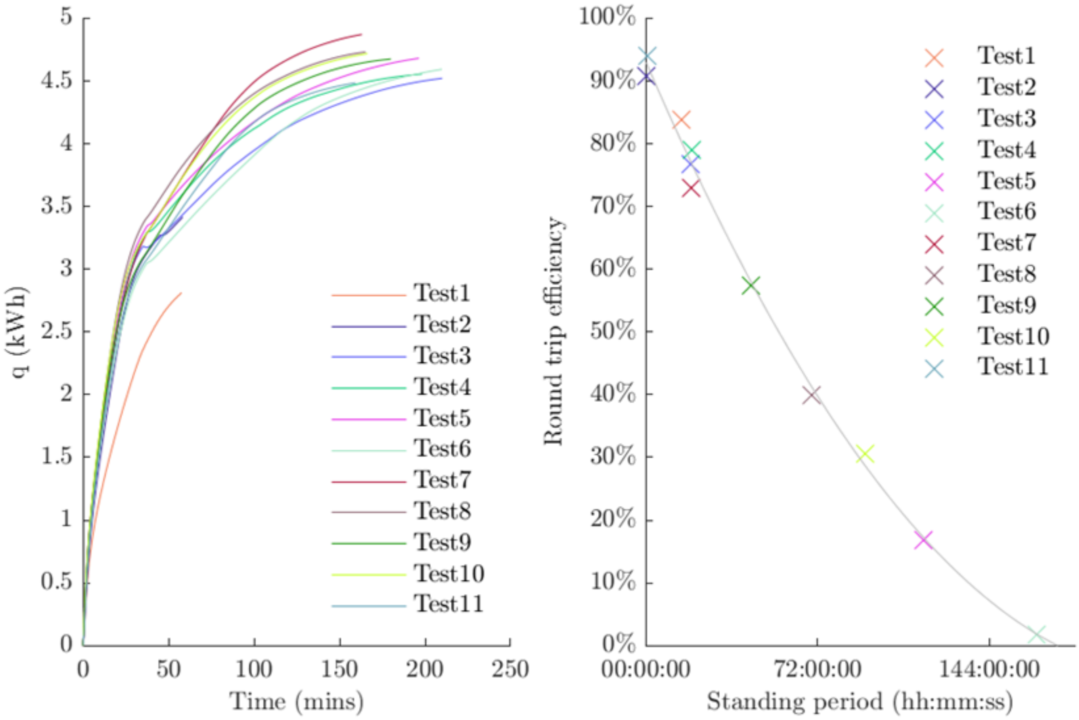

Figure 26**: Charging profiles (left) and round-trip efficiencies (right) for Gen 1 PCM tests.**

The cumulative energy input into the store for each test over time, along with the relationship between round trip efficiency and standing period, are plotted in Figure **26**. The charging process is closely repeatable (excluding Test 1 for which difficulties were encountered in reaching the target charging temperature), and the nominal capacity of 4.5kWh could be reached in a period of around 2.5 to 3 hours. For tests with a short standing period, a high proportion of the stored energy (>90%) could be recovered during discharging. For longer-duration tests (Tests 5 and 6), the standing losses were more significant, with the RTE dropping to around 40% after a 72-hour standing period. The maximum efficiency appears to be over 90%, indicating that the charge and discharge efficiencies may be around 95% each; the remainder of the losses could be attributed to heat lost during the standing period. The efficiencies remain high, at around 70 to 80% for standing periods of 15 to 20 hours, which indicates that the PCM units would be effective in intraday storage applications.

Gen 1 Self-discharge tests

The ability of the PCM units to retain heat when charged was assessed in this suite of tests. The tests were carried out by fully charging the unit (as with the round-trip efficiency tests, the unit was considered fully charged when the temperature sensors had reached a stable value in charge), then disconnecting it from the water circuit and monitoring the unit thermocouples (and the ambient temperature of the chamber) until the unit was fully discharged. The ability of the unit to retain heat in differing conditions was investigated in this phase by setting the ambient temperature of the environmental chamber to controlled levels. For all tests, the unit was charged to 70°C at a flow rate of 5l/min.

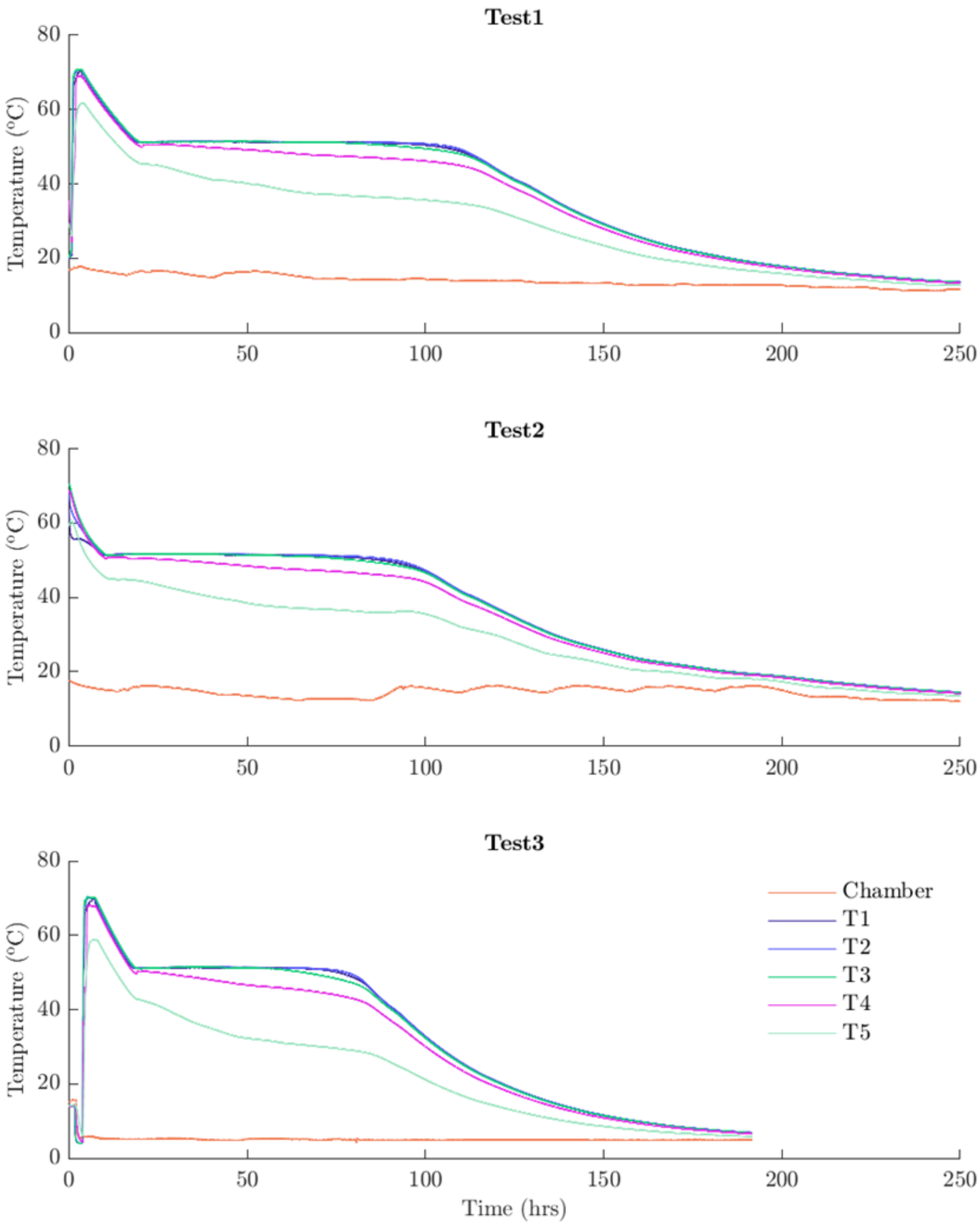

Figure 27: Temperature observed from thermocouples installed on the unit during Gen 1 self-discharge tests. Sensor locations are as indicated in Figure 24.

The results of the self-discharge tests are presented in Figure 27. For Tests 1 and 2, the ambient temperature was not controlled, and can be seen to average between 10°C and 20°C. Test 2 was carried out as a duplicate of Test 1 in order to verify the results observed from the PCM level sensor, the results of which confirmed the belief that the sensor in its current setup was not suitable for these tests. For Test 3, the ambient temperature was set to 5°C using the environmental chamber controls, which is indicative of a scenario where the PCM stores may be sited outside a main building envelope in operation.

For all tests, it is apparent that heat is retained in the unit for a significant length of time, with the temperatures dropping below the phase change temperature at around 100 hours (four days) for Tests 1 and 2. As would be expected, when the ambient temperature is reduced for Test 3, the heat is lost more quickly from the charged unit; the temperatures drop below the phase change temperature at around 75 hours (3 days).

These results are consistent with the findings from the round-trip efficiency tests that the unit holds heat well during standing periods, as a significant amount of heat would be expected to still be available while the unit temperatures are at or above the phase change temperature; this period lasts for around 100 hours for Tests 1 and 2, and around 80 hours for Test 3.

Gen 2 Round trip efficiency tests

The Gen 2 unit was manufactured to the same specification as the units deployed at the CEH trial site. The unit upgrades for Gen 2 pertain mostly to increased insulation to reduce the losses from the unit, alongside a slightly increased volume of PCM within the store. The expected impact of these upgrades was an increase in round-trip efficiency, particularly over longer standing periods as a result of reduced thermal losses from the charged unit. These units were designed to be closer to a commercial offering, with temperature and flow sensor measurements acquired using the unit-level Mixergy controller. Due to the number of available controller input ports, the Gen 2 units were manufactured with significantly fewer temperature sensors installed than had been the case for the Gen 1 units. One thermocouple, T1, was located in the middle of the PCM, in comparison to the six thermocouples placed in the Gen 1 unit.

The recorded data for each test was as per the Gen 1 tests and comprised the flow rate through the rig and a series of temperature measurements For all tests, the unit was charged to 70°C and discharged to 20°C. For these tests, the unit was considered ‘fully charged’ when the internal temperature sensor had passed 69°C and the difference between the inlet and outlet temperatures was less than 1°C. The unit was considered ‘fully discharged’ when the internal temperature sensor had passed below 21°C and the difference between the inlet and outlet temperatures was less than 1°C. The ambient temperature was set to 20°C during these tests. Different standing periods were introduced between the charge and discharge periods for each test, ranging from 34 minutes to 165 hours.

Gen 2 Results

The key performance metric for comparing Gen 1 and Gen 2 designs was the RTE, with attention also paid to discharge profiles. This RTE relationship for both generations is shown in Figure **28**. Gaussian processes (a flexible tool for data regression) were fitted to each set of data in order to visualise the underlying trends and to quantify the level of uncertainty.

The RTE for the Gen 2 unit was significantly greater than for Gen 1 over standing periods of 48 hours or greater, as would be expected given the upgraded insulation. As can be seen in Figure **28**, the gathered data suggests that the Gen 1 unit had slightly greater efficiency than Gen 2 for shorter standing periods, although given the small number of tests cycles conducted this was not deemed to be significant. If more repeat tests were carried out at shorter standing periods, it is anticipated that the average efficiency would be similar for each generation given that performance will be dominated by charge/discharge efficiencies rather than standing losses, and it is the latter that has been the focus of design changes.

Based on the intended use of the PCM units, it may be that the increased insulation is not a useful improvement given the associated increase in the size of the unit. If the units are to be used over intraday storage periods, then no significant performance improvement was achieved for Gen 2. However, in the longer-duration storage case, there is a clear benefit in the additional insulation despite increased volume.

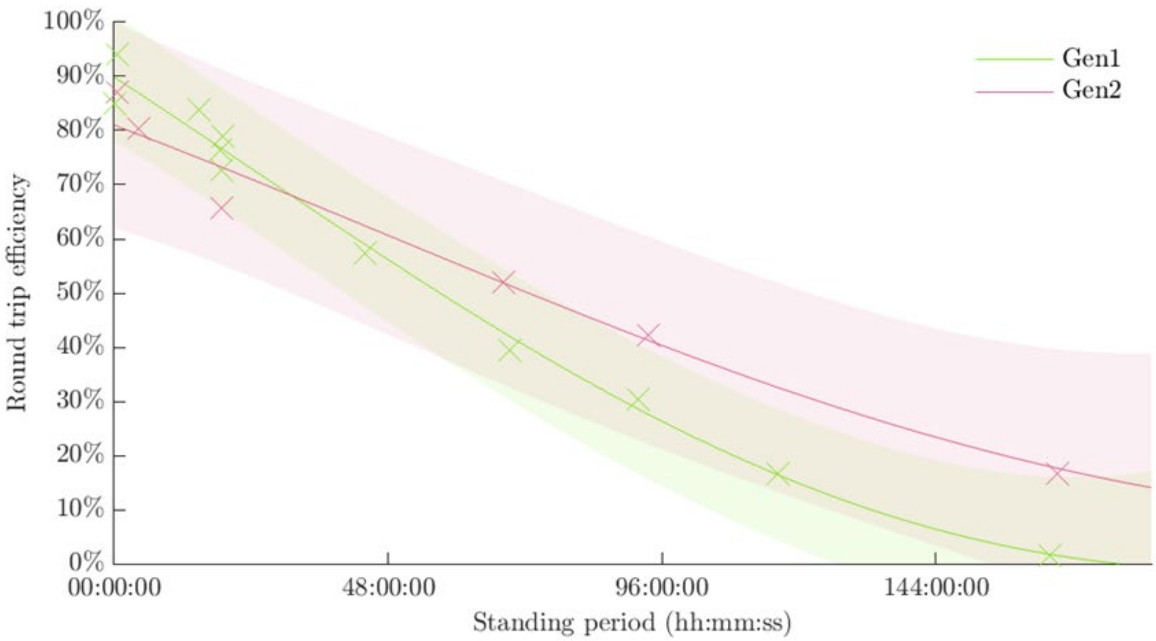

Figure 28**: Gaussian process (GP) fit to RTE values calculated for the Gen 1 and Gen 2 PC units. Markers indicate test observations, the solid line indicated the mean prediction of the GP, and shaded area indicate a confidence bound (±2 standard deviations).**

The discharge profiles for the Gen 2 unit are plotted in Figure 29. It is apparent from this figure that three distinct profile types can be identified. The first profile, which fits the results for Tests 1 and 2, includes a sharp initial peak of above 14kW, followed by a steadier discharge period around 10kW that declines to zero over time. The second profile, which can be attributed to the results from Tests 3–5 is similar but lacks the initial sharp peak. The final profile, which fits Test 6, is of similar shape to the second profile, but with a significantly reduced peak power.

These profiles can be explained to a certain extent by the internal temperature measurement, T1, at the point of discharge for each test. For Tests 1 and 2, which fitted Profile 1, T1 measured significantly greater than the phase change temperature of the PCM, which implies that the initial peak in this profile is caused by the rapid discharge of sensible heat above the transition temperature. For Tests 3 to 5, T1 was observed to be close to the phase change temperature of 53°C, which explains the lack of the initial peak in Profile 2 as there was no significant sensible heat to discharge. For Test 6, T1 was observed to be significantly below the phase change temperature, with observed discharge power profile consequently observed to be significantly reduced. Based on these observations, it was deemed likely that T1 at the time discharge is initiated could act as a useful indicator of the heat recoverable from the unit. This is explored in more detail in the State of Charge (SoC) estimation section.

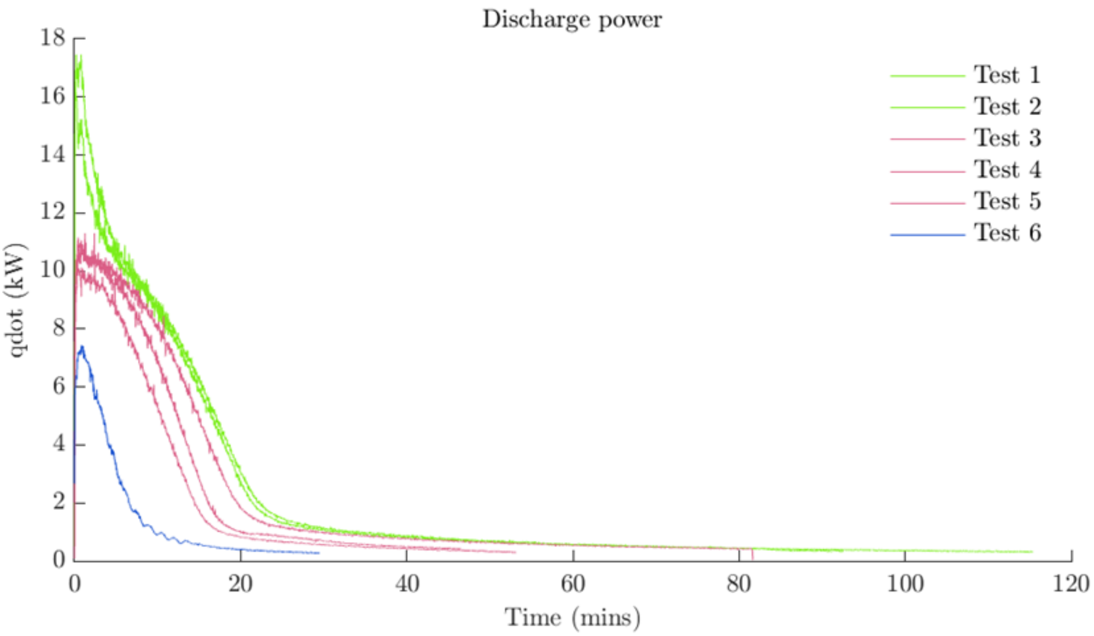

Figure 29: Discharge power profiles for the Gen 2 unit grouped by initial PCM state: liquid (green) transition (red) or solid (blue).

Gen 2 Controlled discharge tests

While understanding maximum charging and discharging powers is important, it is arguably not representative of how the stores are expected to operate in practice. When used for space heating applications, for example, the desired behaviour would typically be to provide a given flow temperature and temperature delta (i.e. difference between flow and return temperature) for an extended period. A sequence of tests was conducted to evaluate the ability of the developed stores to deliver this behaviour. This required modification of the control paradigm for the test rig, with a target temperature delta that was maintained by modifying the flow rate through the PCM heat exchanger: if the temperature delta exceeded the desired level the flow rate was increased and vice versa.

For these tests, the target temperature delta was set to 10°C. The maximum flow rate available for control purposes was 6l/min, imposed by the maximum pump power, with the minimum set to 3.5l/min, determined by the lower limit of the flow meter used for control. During discharge, a target flow temperature from the unit was set, and the discharge was halted when the flow temperature dropped to 5°C below this. Two tests are presented, with the intention to approximate a domestic space heating arrangement: Test 1 with flow/return temperatures of 45°C/35°C respectively, and Test 2 with 50°C/40°C flow and return. The ambient temperature was controlled at 20°C for each test, and there was no standing period between charging and discharging. The unit was charged to 70°C in both tests.

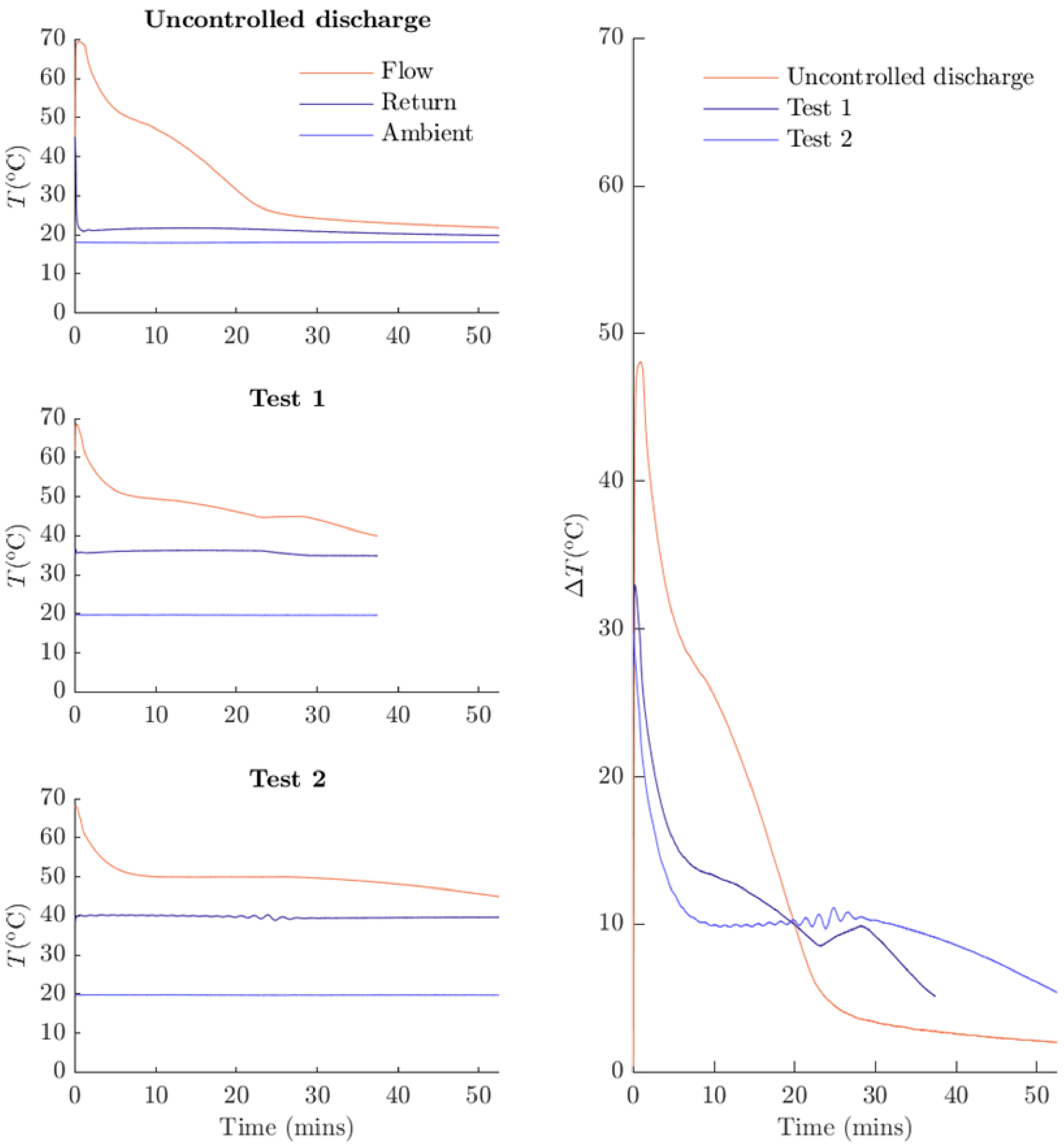

Figure 30: The circuit temperatures for the controlled discharge tests compared to an uncontrolled discharge.

The results of the two tests are shown in Figure 30. It can be observed that a completely steady temperature delta of 10°C could not be held despite the flow controls, particularly during the initial discharge of sensible heat from the unit. However, it is apparent that heat can be extracted close to the target temperature and that this allows for a longer period of high-grade heat extraction compared to the uncontrolled discharge, particularly for Test 2. The temperature delta could be maintained for about 35 minutes for Test 1, and for about 50 minutes for Test 2. These results indicate that the PCM stores could make a useful contribution in space heating applications, particularly when deployed in a modular setup. If three PCM modules are deployed, as is the case at the CEH trial sites, then consistent heating output could be provided for around 2.5 hours. This would represent a substantial contribution to covering evening peak periods, noting the current Octopus Cosy tariff features a 3-hour peak period from 4pm to 7pm.

Outcomes

The work conducted at the LVV has successfully provided detailed characterisation data on the two generations of PCM store developed by CREST. This work represents a valuable step forward in the understanding of the performance of the system in idealised conditions, enabling upper bounds on storage capacities, round trip efficiencies and charge and discharge powers to be established. The exploration of RTEs and power outputs following extended standing durations of up to 165 hours (approximately one week) is a contribution of particular value. All tests were conducted in controlled environmental conditions, increasing confidence in the comparability of the recorded outputs.

Key conclusions are summarised below:

- For both generations, RTEs in the range 85 to 95% were observed for short duration (i.e. immediate charge-discharge) tests. Comparatively high RTEs were observed for “medium” duration tests, with a mean of 75% RTE observed for tests with a standing duration of 12 to 18 hours.
- The Gen 2 store demonstrated greatly improved RTEs over extended (>24 hour) duration tests. However, this improved long duration performance came at the expense of a lower overall energy density due to the additional insulation added.
- Recoverable powers in the range of 2 to 18kW were observed for the first 20 minutes of discharge during maximum discharge tests, followed by output powers of over 500W for up to two hours, representing a useful contribution to heating loads within domestic properties. It is noted that multiple stores may be installed into a property in order to scale up output. Subsequent controlled discharge tests enabled output at a near constant temperature delta of 10°C over a period of 50 minutes to be demonstrated.
- Recoverable energy capacities of up to 4.5kWh were demonstrated when discharge was conducted from an initial internal temperature of 70°C to a final internal temperature of 20°C. Operation over a narrower temperature bound focused on the phase transition temperature (~53°C) would likely be preferable in practice. This would reduce both the amount of energy used to charge the store and the energy ultimately recovered. It is expected that this would have a beneficial effect on RTE due to (i) lower losses incurred

when charging from the "cold", solidified state and (ii) reduced standing losses when the PCM is in its "hot" liquid state. This would come at the expense of a reduction in the effective energy storage density of the units.

Low Carbon Laboratory (LCL)

The main aim of the Low Carbon Lab (LCL) is to enable testing of low-carbon SH and DHW systems with integrated thermal energy storage (TES) units in a controllable environment. The experimental setup within the Low Carbon Lab (LCL) rig mirrors and extends upon the systems installed into the Creative Energy Homes (CEH), enabling demonstration and optimisation of the thermal storage devices and related control systems for a range of alternative heat sources and in multiple system configurations. A schematic of the rig is shown in Figure 31, with the location of the heat meters (labelled 68 to 71) being relevant to the work presented in this section. System control mirrors that implemented at CEH, with software hosted on the lab PC acting as the Main Controller for the system. This software manages the scheduling of the operational modes of the system i.e. charging, discharging or idle state of the thermal storage systems, and handling the related actions (i.e. calls for heat from the heat pump; operation of valves and pumps). All testing data (system temperatures, flow rates etc) alongside logging outputs from the controller (modes of operation, PCM inlet/outlet power calculations) were continuously monitored and uploaded to Open Energy Monitor's EMonCMS server via an online data logger, enabling access and analysis via API calls. The work covered in this section progresses from initial testing of a single PCM units; through more detailed performance evaluation following as set of system improvement; and on to extensive testing of PCM stores in two- and three-unit configurations.

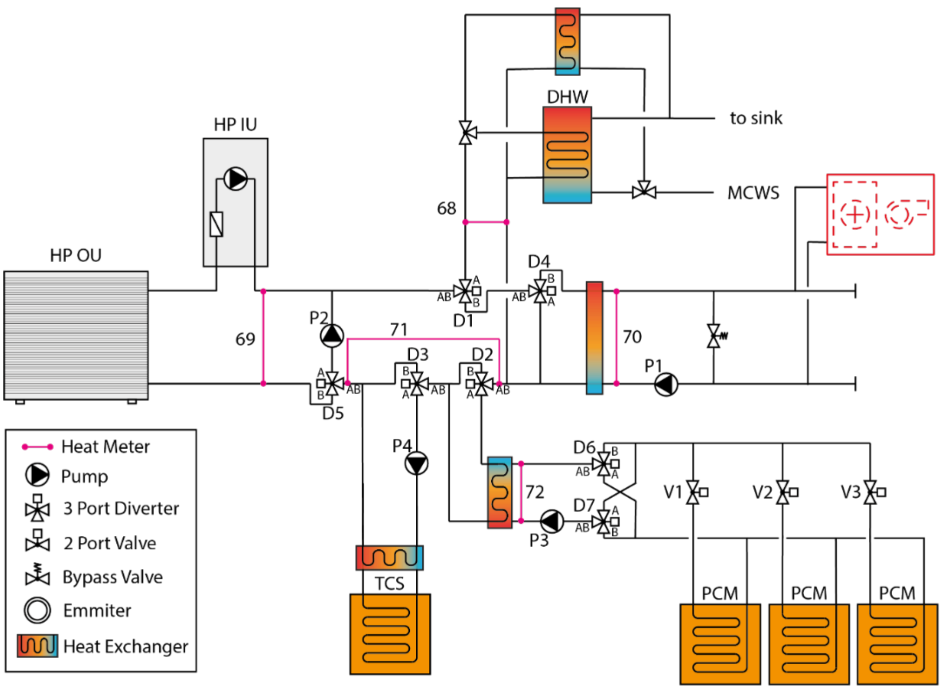

Figure 31: Schematic representation of the Low Carbon Laboratory system.

Technical outputs

Round trip efficiency quantification

Two different PCM configurations were tested in this work: two PCM units connected in series and three PCM units connected in series. The decision to focus on charge/discharge of multiple units was motivated by observations made during an initial, single-unit testing round. It was observed that when charging the stores, the heat pump output would peak at around 8kW and then drop significantly before recovering. It was initially believed that this behaviour arose from the limited modulation range of the heat pump, allied to the fact that a single store was being charged compared to the three being simultaneously charged at CEH. This learning led to exploration of alternative modes of system operation that will allow the heat pump to operate within its modulation range. The multi-store tests ultimately revealed that this issue arose from limits on operational duration applied by the heat pump controller.

For both configurations, the charging objective was set to the mid-temperature of 55°C (2°C higher than the melting temperature of PCM used) to ensure that the material inside the units was completely charged at the end of a charging process. The charging process was started when the PCM mid-temperature reached approximately 35°C for all tests. The discharging process was conducted by transferring the energy in the charged PCM units to the hot water tank. In all cases, the initial state of the hot water tank was to contain water at the mains supply temperature, with the hot water in the tank emptied after each discharge. The discharging process was considered complete once (i) the mid-temperature fell below 35°C and (ii) the power discharged by the controlled unit fell below 1kW, for the two-units configuration. These limits were respectively 40°C and 1kW for the three-units configuration. These values were arrived at heuristically through initial testing and adopted to allow consistent evaluation within the trials, but there remains scope for more rigorous evaluation and optimisation of start/stop conditions. It should be noted that the flow rate, mid-temperature, flow temperature and return temperature of just one PCM unit were the controlled variables for charging/discharging objectives as there was only one PCM controller in the setup. The external temperatures during the testing period lay in a consistent, low range with a minimum of -3°C and maximum of 8°C observed.

Testing of two PCM units connected in series

Table 2 summarises the performance metrics of the two-unit configuration measured across various charging/discharging cycles. It was observed that the PCM round trip efficiency is >0.8 for short periods of standing duration, with values greater than 0.9 typically observed. For prolonged standing durations (see Cycles no 5 and 7), the efficiency drops to around 0.5 due to significant overnight thermal losses. The mean heat pump COP was found to be 2.0 (minimum 1.85, maximum 2.1) across the 9 cycles.

Table 2: A set of performance results from two-units configuration testing.

Cycle no	Cycle start date	Standing duration [hours]	Energy charged [kWh]	Energy discharged [kWh]	Electricity spent for charging [kWh]	PCM efficiency [-]	Heat pump COP [-]
1	14/01	0.05	4.35	3.98	2.14	0.91	2.03
2	14/01	0.02	4.40	4.01	2.08	0.91	2.12
3	14/01	0.05	4.39	3.94	2.17	0.90	2.02
4	15/01	1.00	4.31	3.59	2.09	0.83	2.06
5	15/01	16.5	4.35	2.16	2.15	0.50	2.02
6	16/01	1.70	4.14	3.56	2.18	0.86	1.90
7	16/01	18.5	4.24	1.73	2.10	0.41	2.02
8	17/01	0.05	4.16	3.84	2.09	0.92	1.99
9	17/01	0.05	4.35	3.86	2.35	0.89	1.85

Testing of three PCM units connected in series

Figure 32 illustrates the performance of the three-unit configuration across a set of 23 charge/discharge cycles. The PCM RTE was observed to be >0.8 for short standing durations. For prolonged standing durations, the PCM RTE decreased to around 0.5 due to significant overnight thermal losses. These results were consistent with the findings for the two-unit configuration. Similarly, the mean heat pump COP was found to be 2.0 (min 1.8, max 2.3) across the 23 cycles, indicating consistency with the two-unit and three-unit configuration. The nominal charge temperature was held constant at 55°C.

Several observations were made for the three-unit data. The first of these was that the observed RTE was found to be significantly lower for the first cycle performed within each day (shown in red in Figure 32) than for subsequent cycles (shown in blue). This bears further investigation, but the working assumption is that this may be ascribed to the energy lost in bringing the system up to standard operating temperatures after being allowed to settle to ambient temperatures overnight.

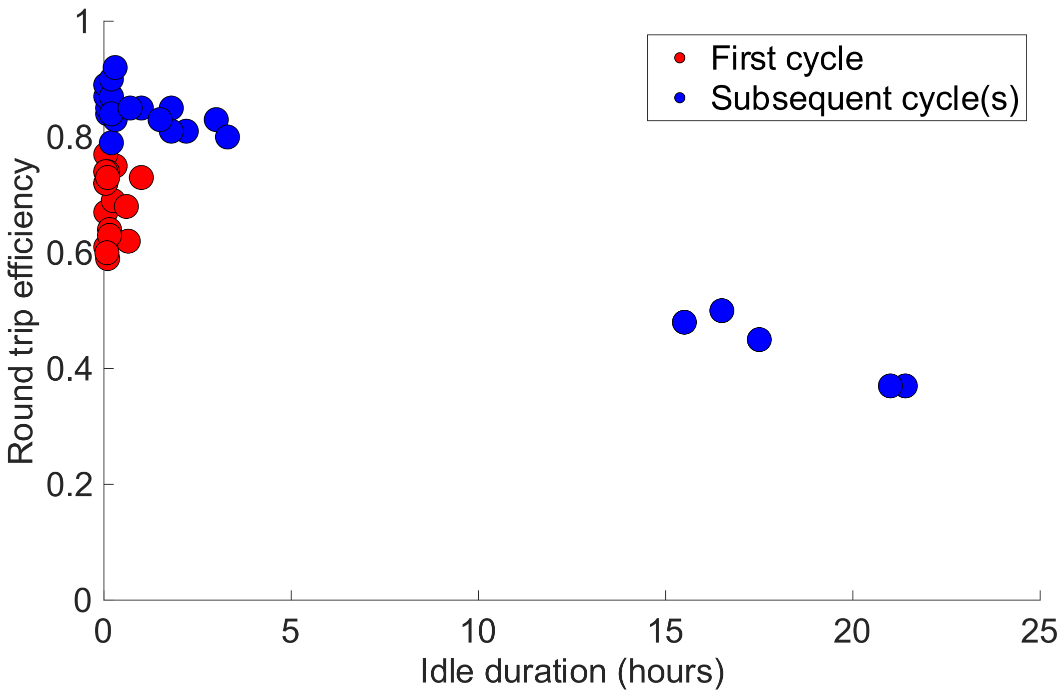

Figure 32: Calculated RTEs for all charge-discharge cycles of the PCM system tested in three-unit configuration. Observed RTEs were found to be markedly lower for the first cycle performed within each day (red) than for subsequent cycles (blue).

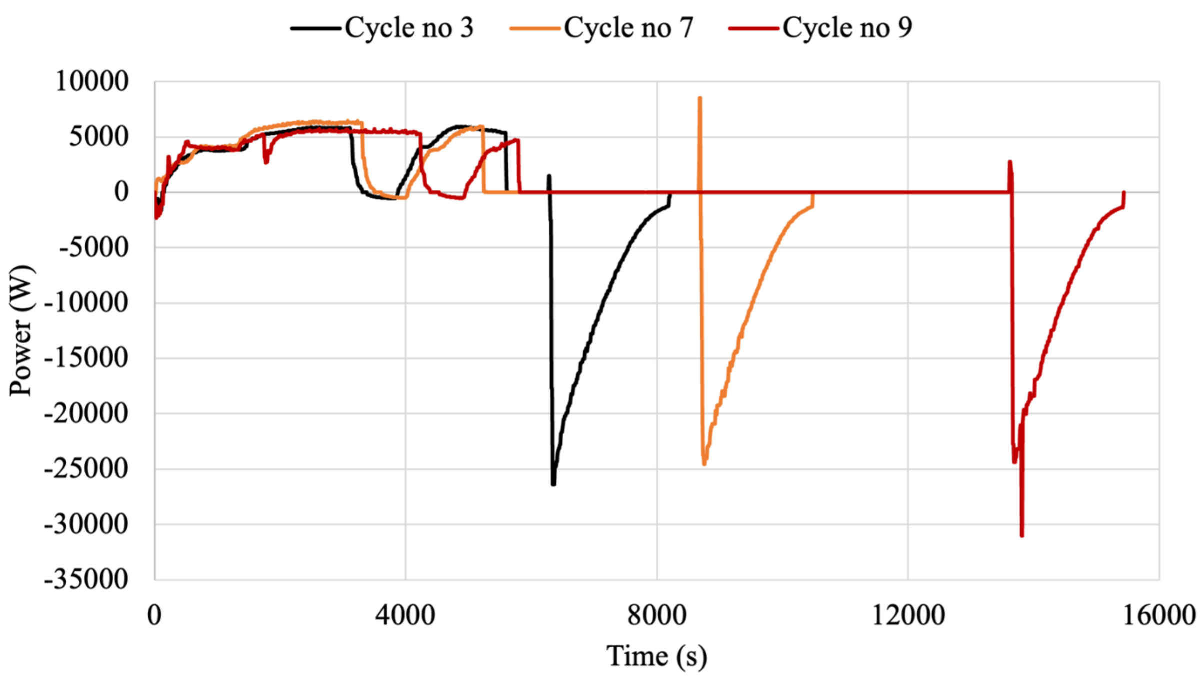

Figure 33: Charge-discharge profiles for the three-unit system setup, for three exemplar cases.

Secondly, a distinction observed from the two-unit configuration testing is that all of the three-unit test cases produced a somewhat unusual charging profile (i.e. with a discontinuity in the heat pump operation). This is exemplified for a subset of cycle profiles in Figure 52, with the heat pump output power (and subsequently the PCM unit input power) dropping to zero for a period in the 3000 to 5000 second range. This is believed to arise from the control rules implemented within the heat pump controller; it is common for these to include shutdown of the compressor after a period of low output. Overcoming such behaviours will involve deeper understanding of the heat pump controller such that interoperation of the heat pump and store may be optimised.

Outcomes

A set of system-level PCM characterisation tests was carried out in a laboratory environment intended to mirror that experienced in the trial homes at CEH. The primary PCM discharge mode was to the domestic hot water tank which was itself discharged down to the temperature of the main supply water before each PCM discharge cycle. Three different PCM configurations (single, two-in-series, three-in-series) have been tested to investigate the effect of PCM volume increase on the efficiency. Regardless of the PCM volume, it has been found that the PCM round-trip efficiency stays higher than 80% up to two hours of standing period. This supports the view that PCM technology would be significantly cost-effective if the off-peak electricity times are used for charging. It should be noted that even though some tests show lower efficiencies, these are the first tests that have been performed in a day and PCMs have been charged from a lower temperature than the latter tests of the day (and the temperature of the main supply water) to the target temperature. However, the calculated round-trip efficiency was observed to decrease to lower than 50% for standing periods in excess of 12 hours. This reduction in calculated RTE was significantly greater than that observed when testing the systems in isolation within the Laboratory for Verification and Validation (LVV), where RTEs of 50% were observed after 96 hour standing periods. This supports the finding that there is scope to achieve substantial improvements in storage performance through (i) simplification of the hydraulic system design and (ii) addressing interoperability with the heat pump.

Lessons learned

- **Pressure loss through heat exchangers was considerable.** Future heat exchangers should comprise smaller elements linked in parallel. Stores can be scaled in multiples of heat exchanger unit size based on loads.
- **Weight of stores for transport and installation.** Stores to be filled with PCM on site to reduce weight during transport and installation at site.
- **Need for hydraulic separation.** Potential for melted PCM material leaking into the hot water circuit.
- **Create single integration point with domestic systems.** To make installation straightforward as possible.
- **Control of the heat pump's main circuit pump.** In the current configuration there is limited control of the main pump. Additional control systems are required to gain further insight and operation of the main pump for other purposes/functions. An additional

Modbus controller within the heat pump unit would give Mixergy more information on what the heat pump unit is doing at any given moment.

- **PCM to DHW.** If DHW cylinder does not experience a large draw-off during the morning period the PCM energy transfer is limited. Heat pump still has to work to reach the desired setpoint temperature.
- **PCM to SH.** There is greater discharge potential in the larger space heating circuit in both homes. This has priority over DHW production as the heat pump can quickly heat the DHW cylinder as required.
- **Near freezing outside temperatures resulted in critical errors when PCM discharge was initiated.** The heat pump must be able to carry out the anti-freezing cycle independently of other system operation.
- **Lower PCM phase change temperature**. A lower PCM phase change temperature would be ideal and increase heat pump's efficiency.
- **Reduced RTE observed for first test of the day**. The (artificially) low efficiency tests show that the PCM round-trip efficiency calculation needs a consistent approach as the low efficiency tests cannot be compared with others.
- **Heat pump interoperability.** It was observed that some stopping criteria applied when charging the stores (such as continuing charging until a minimum power threshold was observed) led to charge durations of sufficient length to trigger time out/shut down of the heat pump. This was observed to cause partial charging of stores on several occasions, and a subsequent reduction in RTE.

Conclusions

Stores have been designed, manufactured, characterised under lab conditions and installed and tested in test houses. When charging the store to 70°C, 10kWh of heat is deliverable at temperatures of over 50°C suitable for either domestic hot water or low temperature space heating. The initial modular design of the store was selected to enable the option of increasing or decreasing the number of stores to enable different domestic heat loads to be met, i.e. two modules if a 6.6kWh store was needed, three for a 10kWh store. Prototype stores had three significant cost elements, heat exchangers, phase change material and module enclosures with a combined cost of approximately £4000 per three-module store split approximately equally between the three cost elements. With large scale manufacture, cost reductions should be possible in all of these areas. Based on payback period calculations, costs and examined use scenarios, costs need to be reduced significantly to below £2,000 per store or number of cycles annually need to increase above 120.

Thermochemical store (TCS)

The aim of this work was to bring the technology to TRL7 through successful demonstration of the devices in an operational environment. The technology was developed from an initial TRL4 with a reduced-scale prototype having been validated in a laboratory environment. Successful demonstration of this first-of-a-kind technology in a domestic environment was deemed an ambitious but achievable goal.

The key objectives pursued within the TCS workstream are given below:

- Manufacture and characterisation of Gen 1 prototype systems at CREST. The target storage capacity of each Gen 1 system module was 50kWh.
- Design and manufacture of a set of Gen 2 storage system, based upon learnings from deployment of the Gen 1 systems.
- Delivery and installation of storage and associated control systems at four trial sites.
- Monitoring and evaluation of performance of the systems in an operational environment at CEH.
- Characterisation of the TCS stores in an independent test environment at the LVV.
- Development of a Gen 3 store design based upon learnings across all trial sites, including an assessment of the commercial case for this proposition in a domestic environment.

Centre for Renewable Energy Systems Technology (CREST)

The work at CREST covered four main elements: characterisation of a lab-scale TCS rig to refine the system design; design, manufacture and characterisation of two generations of full-scale TCS store; and design of a proposed third generation informed by project learnings.

First, an automated lab scale TCS test rig was designed, fabricated, instrumented and characterised using a Huber thermal control unit to circulate heated oil through the heat exchanger. Lab scale experimental results gave confidence that the heat exchanger was suitable to both charge and discharge the store and that high temperatures were generated in the TCS bed during discharging.

Based on the lab scale rig, a 50kWh ‘Gen 1’ TCS system was designed and built by the CREST team, employing a larger scale version of the developed heat exchanger to provide good rates of heat transfer to and from the store. To reduce pressure losses through the heat exchanger, a low viscosity water-glycol fluid was used in preference to a heat transfer oil within the charge/discharge system. Mixergy designed and installed a control and power supply system with data logging functions.

A key finding from deployment of the Gen 1 stores at CEH was that they were difficult to transport and install due to their size (1.8m tall) and weight (450kg). To address this, the second generation stores were reduced to 25kWh capacity, halving their height and weight.

Designs for a Gen 3 store were developed following a financial analysis which indicates that 100+ charge/discharge cycles are required with capital costs of 100 £/kWh or less to achieve payback of investment costs within ten years based on likely tariff differences. The Gen 3 design is for a smaller application store size of 10kWh more suited to high numbers of cycles.

An important note regarding both the Gen 1 and Gen 2 stores is that they were designed to meet Sound Engineering Practise (SEP) guidelines, which resulted in store enclosures with large thermal mass. Similarly, the Pressure Systems Safety Regulations 2000 (PSSR) impose restrictions on admissible temperatures and pressures for relevant fluids. To comply with PSSR without the need for pressure vessel certification, we adopted a reduced maximum charging temperature (<110°C) and store pressure (<0.4 bar gauge). Certification is a lengthy process that would not have been achieved within the project timescale but would be pursued for commercial units. The temperature restriction imposed by PSSR was found to substantially limit the charging rate and usable storage capacity of the TCS systems.

Technical outputs

Lab prototype testing

Thermo-chemical storage systems store energy in a reversible chemical reaction. Our design is “charged” by adding heat through a heat exchanger to dehydrate the storage material. The water vapour driven off is removed by reducing the pressure in the store and stored separately. To discharge the store, water is reintroduced into the store to react with the storage material. This reaction generates heat that can be removed and used for heating purposes.

The lab scale TCS system was based on a 1m tall cylindrical store with an internal diameter of 203mm with a 5kWh thermal storage capacity. The experimental rig was automated with valves and vacuum pump controlled by relays activated by signals from a programmed microcontroller. A finned heat exchanger design was developed, manufactured and installed in the TCS test rig. 12 temperature sensors were installed to allow observation of temperature dynamics at a subset of locations within the store. These were arranged as three columns of four sensors at different heights from the base of the store (0.8m, 0.56m, 0.33m and 0.1m).

Lab scale system charging

The TCS material in the lab scale store was put through a short duration, 100-minute charging (heating) process with heated oil circulated through the heat exchanger. The store was initially in a part discharged state following earlier partial charges and discharges. The inlet oil temperature, outlet oil temperature and calculated rate of power input to the store are presented in Figure 34. The store was not insulated during this charging process, with heat losses expected to be negligible during the short duration of the test due to the low temperatures of the store enclosure. The charging process transferred a total of 0.78kWh of heat to the store.

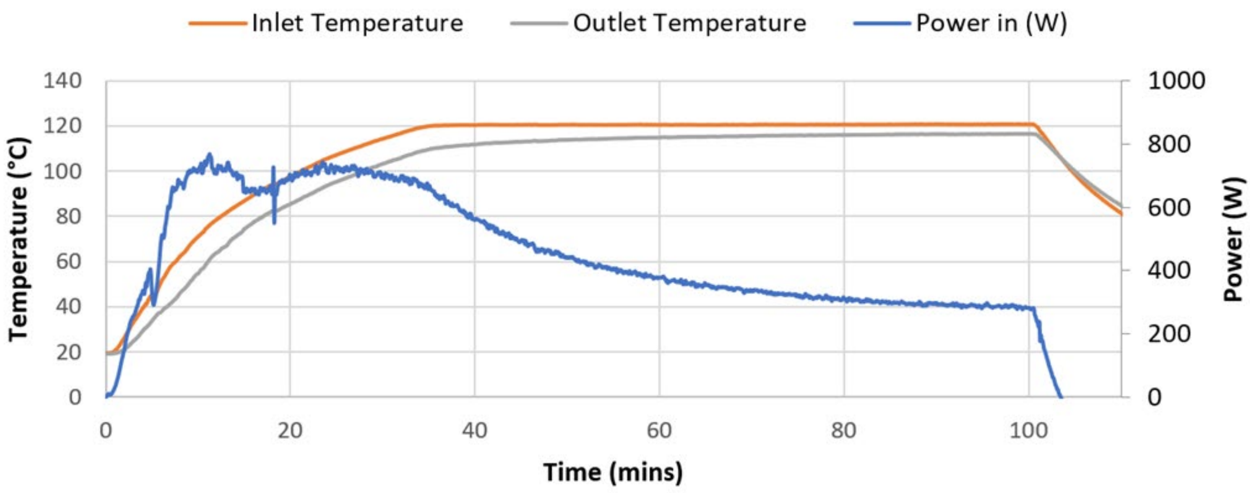

Figure 34: The measured inlet and outlet oil temperature and the calculated rate of power input to the store.

Figure 35 shows the measured temperature within the TCS stores at the 12 thermocouple locations as it was heated (charged). The measurements from thermocouples at locations 1, 2 and 3 are indicated indifferent shades of blue, orange and green dependant on depth within the store. To achieve a good level of charge all of the TCS material should reach a temperature of over 100°C. Recorded temperatures and power input rates indicate that TCS stores will require insulation and a long charging period. The initially high charging rates of power input are due to the temperature difference between the TCS bed and heat transfer fluid.

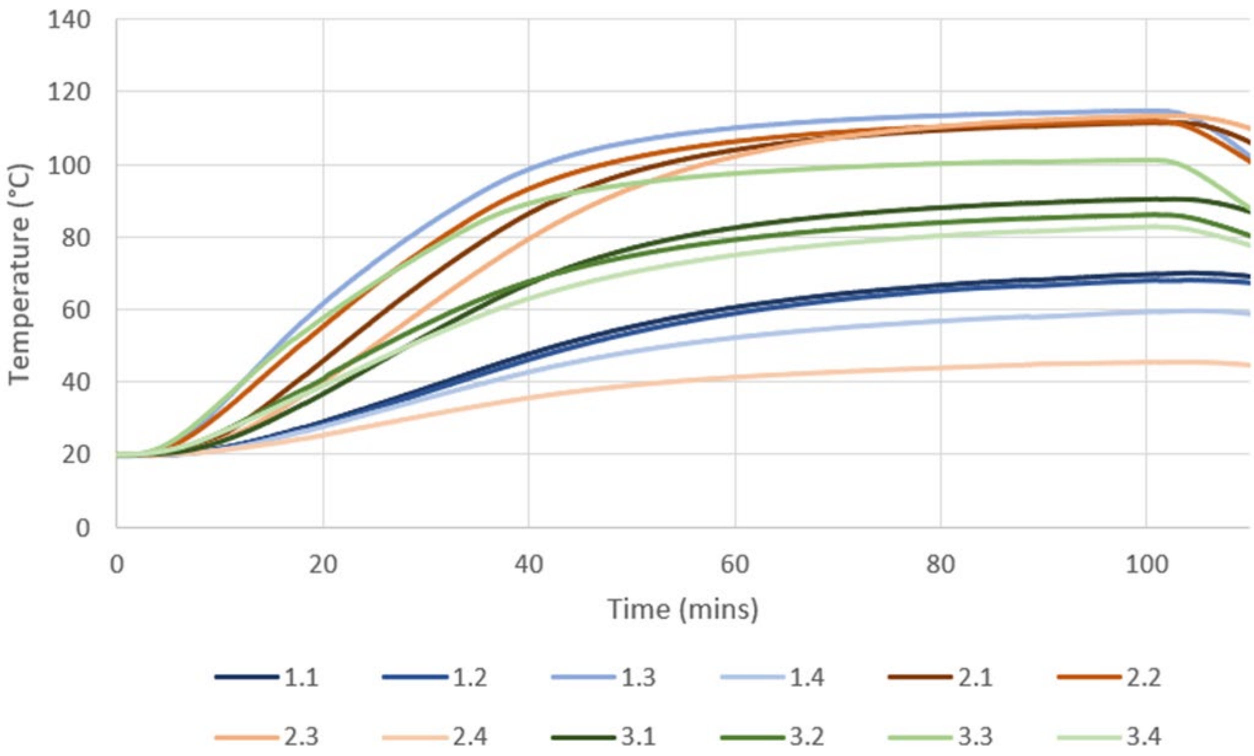

Figure 35: Temperatures measured by thermocouples at heights of 0.8m, 0.56m, 0.33m and 0.1m from the base of the store for three cross-sectional locations.

Lab scale system discharging

The store cooled to ambient and was then insulated before discharging. During discharging water was injected intermittently on to the top of the TCS bed in the store.

Figure 36 presents the temperatures measured by the 12 thermocouples within the TCS system as it was discharged in phases. The red line on the graph indicates the estimated percentage state of discharge. The TCS material responds quickly during the discharging process. At 21 minutes an 8% discharge was instigated by introducing water to the store with an almost immediate temperature rise recorded from sensor 3.4 which peaks at 262°C. While this temperature response shows the potential of the material to achieve high temperatures, a localised temperature spike is not ideal. The localised temperature peaks measured at different locations within the store, clearly indicate that the store bed is not discharging (releasing heat) evenly. This was addressed for the domestic scale TCS systems by an improved spray system that spread the water evenly.

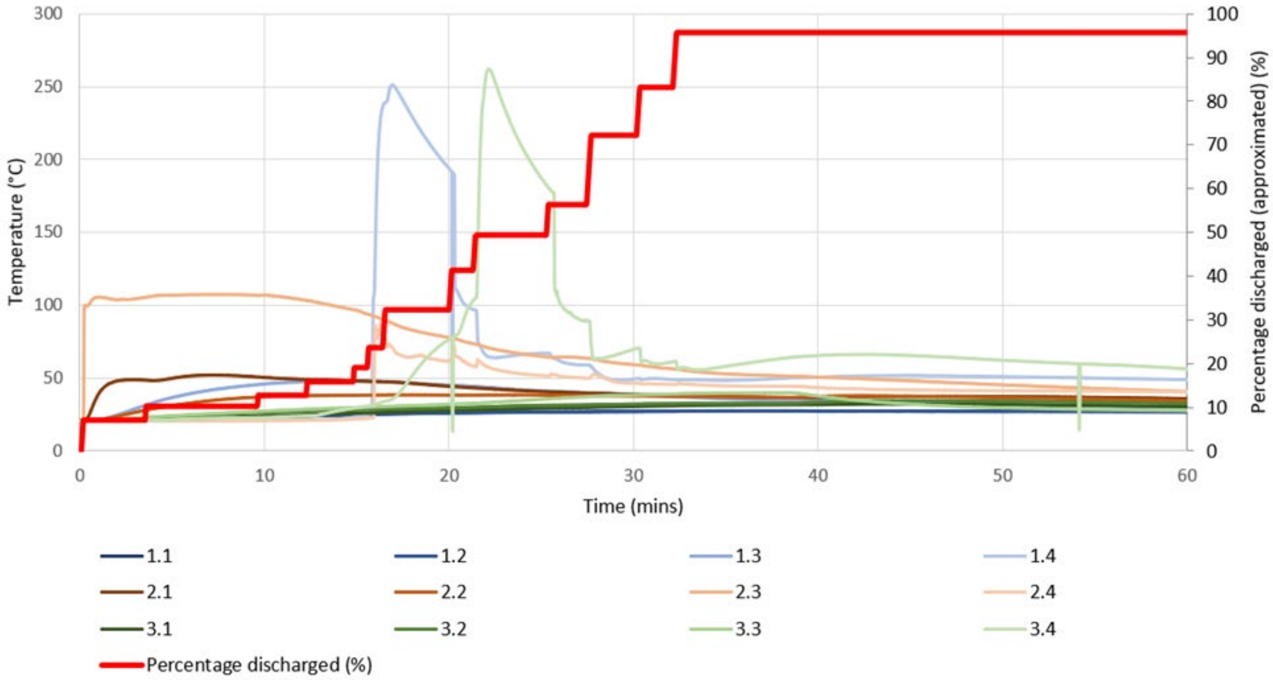

Figure 36: Measured temperatures of the 12 thermocouples with time.

Figure 37 shows the calculated power output and the measured inlet and outlet temperatures from the store during the discharge test. A sequence of controlled discharge events raised the store temperature and the heat exchanger removed that heat from the system. The peak power output was around 630W.

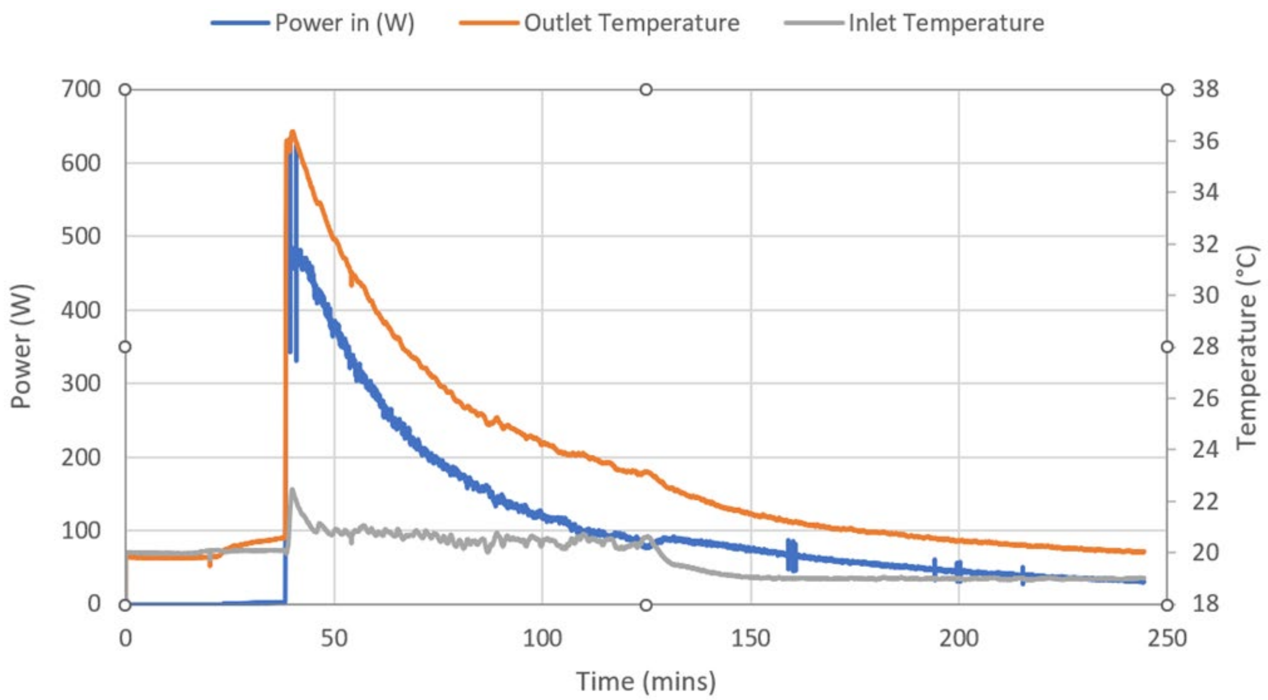

Figure 37: TCS inlet/outlet temperatures and calculated power output during discharge.

From the data collected during the 206-minute duration heat removal phase, the heat output from the store was 0.41kWh, which is approximately 8% of the calculated heat storage capacity of the store when fully charged. This was largely ascribed to the limitations on charging temperature imposed by PSSR, which limit fluid temperatures to <110°C. Previous material characterisation tests have given confidence that high energy storage densities are achievable when the TCS material is uniformly charged to 110°C. To achieve a uniform store temperature of 110°C, the temperature of the fluid in the heat exchanger would need to be at least 120°C (ideally higher) combined with high heat exchanger surface area and high levels of insulation to prevent heat losses from the store exterior surface.

Gen 1 Design and Manufacture

The lab scale system demonstrated the potential of the TCS material to achieve high temperatures and that the heat exchanger was able to transfer heat to and from the TCS bed. The initial lab scale characterisation tests gave confidence that the heat exchanger design, heat transfer surface area/store volume ratio was sufficient to deliver required rates of input and output power. The Gen 1 TCS scales up the lab design to 10 times the volume and capacity.

The 50kWh storage capacity TCS used a cylindrical vessel with internal dimensions of 500mm diameter and 1675mm height. The heat exchanger was made from 36 straight copper pipes, each with fin assemblies.

Figure 38: A Gen 1 TCS vessel connected to heating system and controller at CREST.

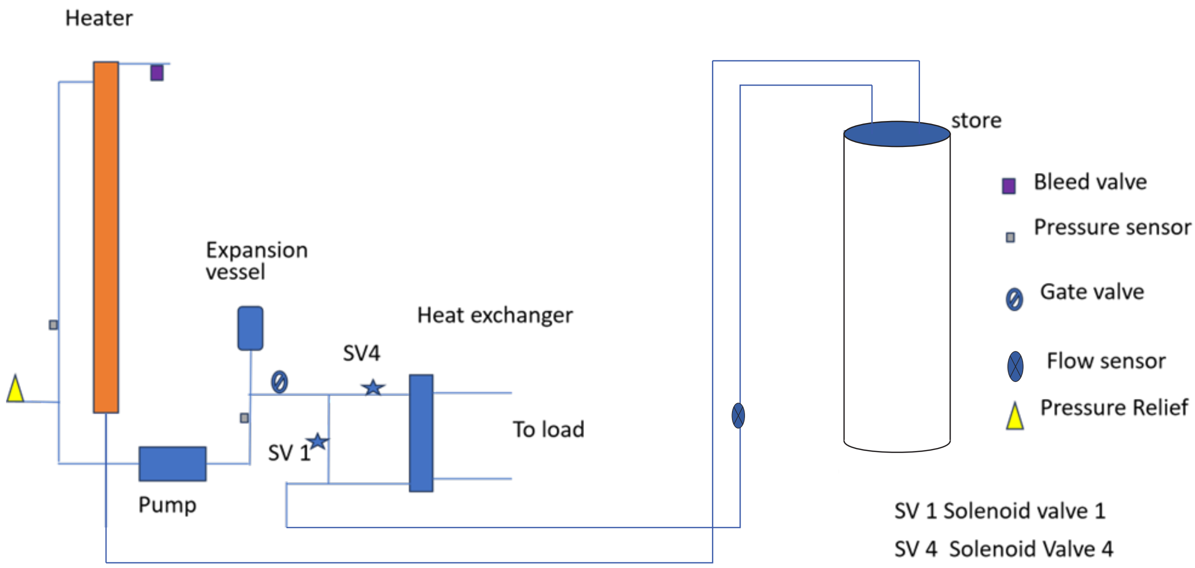

Figure 39: A schematic diagram of the pressurised charging and discharging water glycol loop.

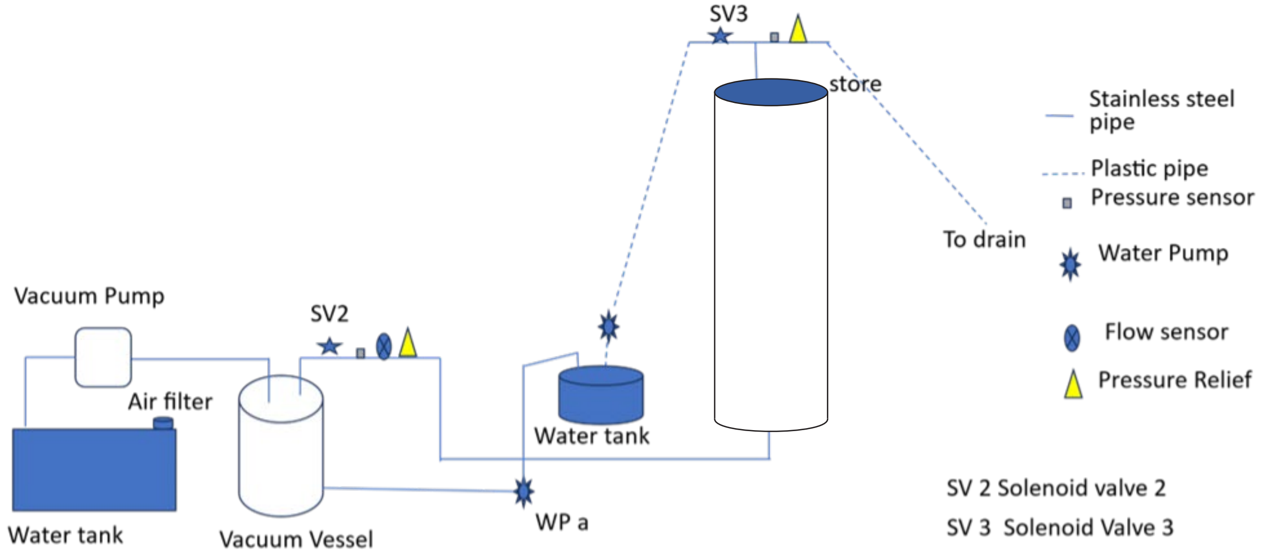

Figure 40: A schematic diagram of the vacuum/water delivery loop for the TCS system at CREST.

The lab system is shown in Figure 38 and the modified test site design in Figure 41. The final schematic incorporating modifications after testing is illustrated in Figure 39 and Figure 40 which includes a thermostatically controlled 9kW heater. Operating the solenoid valves enables regulation of fluid flow path for charging and discharging.

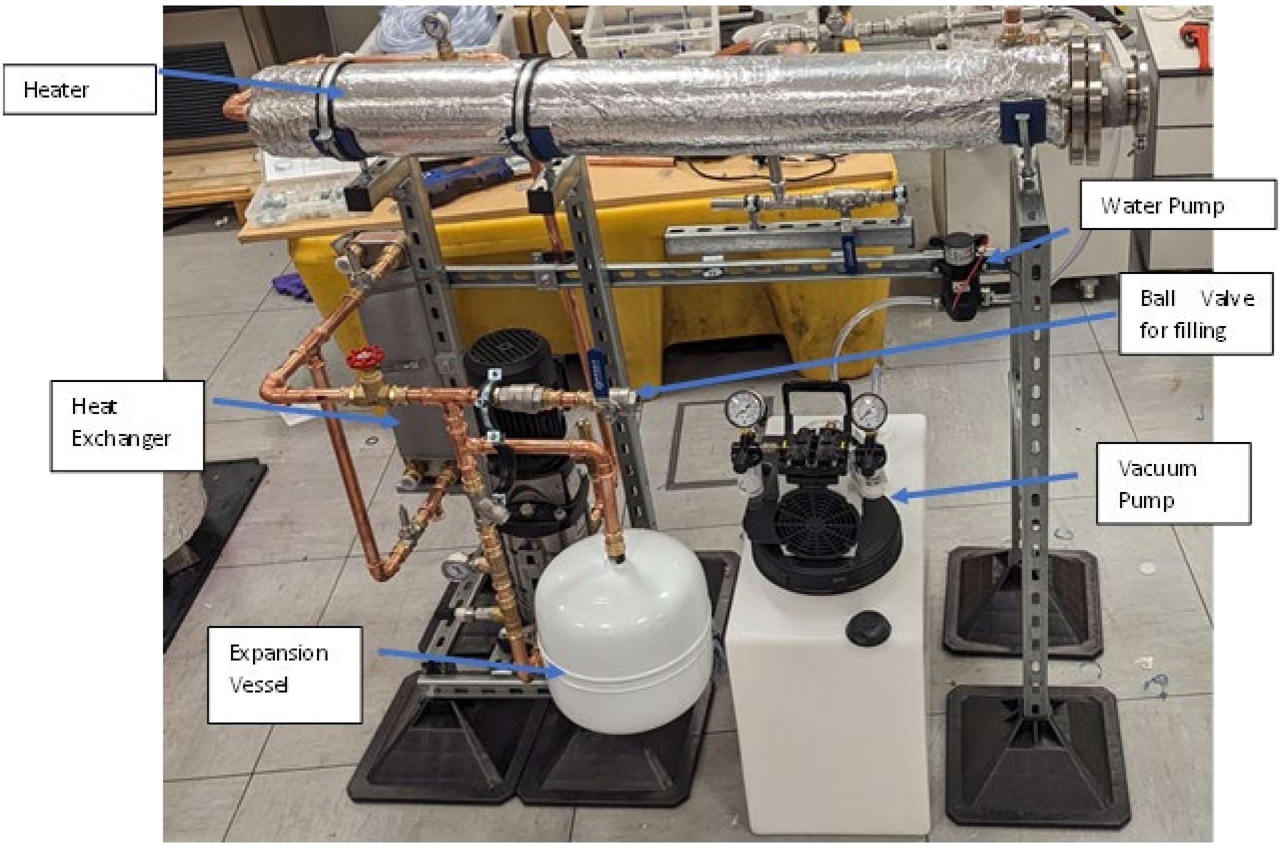

Figure 41: A Gen 1 ancillary heating system deployed to test site.

Modifications incorporated in the test site units included:

- Vacuum vessel to control condensation that occurs in the vacuum pump trap during store charging.
- Horizontal heater to simplify operation with an automatic vent valve, and to ensure that fluid fully covers the heating element.
- Simpler pipe arrangement and more compact design, with better access to the filling loop and liquid-to-liquid heat exchanger.

A number of data acquisition issues were experienced and remedied during the initial charging and discharging experiments, which limited the degree to which quantified conclusions could be drawn. Nonetheless, the following observations were made:

- During the first discharge a rise in outlet fluid temperature to over 60°C was observed, power output rates were initially high, decreasing to approximately 3kW which was sustained for several hours.
- Charging periods required were long with several hours of heat input required prior to water being driven from the store, heater cycling reduced average heat input rates below 3kW.
- Insulation levels were increased on the store and pipe work to reduce heat losses resulting from the high operating temperatures employed.

Gen 1 Experimental Testing

Nine part-charging and five discharge experiments were performed. The part charging experiments conducted were of different durations ranging from 6 hours to 24 hours. The discharge tests were performed with the store part charged. The main findings were that:

- For a flow rate of 8.5 l/min the rate of heat input to the store was initially just under 3kW, until the heat transfer fluid temperature exceeded the set point of 108°C, after this the heater cycled on and off with a regular period delivering approximately 1.65kWh/h.
- Charging the store for 24 hours continuously is more effective than charging for three 8-hour periods with breaks in between, driving greater volumes of water from the store.
- If stores are only charged for short periods of time, sensible heat input is a significant part of the energy stored which if lost reduces efficiency significantly.
- To obtain high temperatures in the store during discharging stores need to be charged to over 50% capacity.
- During the start of discharging there should be no flow through the heat exchanger so that bed temperature can rise.
- Temperature sensors in the bed of the store are required to determine when discharge fluid flow should commence.
- Higher outlet temperatures can be obtained during discharging if flow rates are low.

- High rates of power output can be obtained if discharge follows soon after charging with good round trip efficiency.

Due to the charging temperature being limited to 110°C, the rate of heat transfer to the store is restricted when the bed temperature around the heat exchanger rises. This was addressed by maintaining the heat exchanger at 110°C for a long period of time until all of the bed reached 100°C.

Inlet and outlet temperatures to the store were measured for the charging experiments of a Gen 1 TCS system after full discharge with a flow rate through the heater and store heat exchanger of 8.5 l/min. Minute-averaged data is presented in Figure 42. This shows an initial rapid temperature rise to 60°C of both inlet and outlet for approximately 20 minutes, followed by a slower rise until the heater control set point temperature of 108°C resulted in on/off cycling of the heater. Instantaneous energy input rate and the cumulative energy transferred to the store were calculated. The heat transfer rate to the store in the initial 20 minutes appears to be greater than 3kW, after 20 minutes the rate of heat input falls to 2.6kW which is in the range expected.

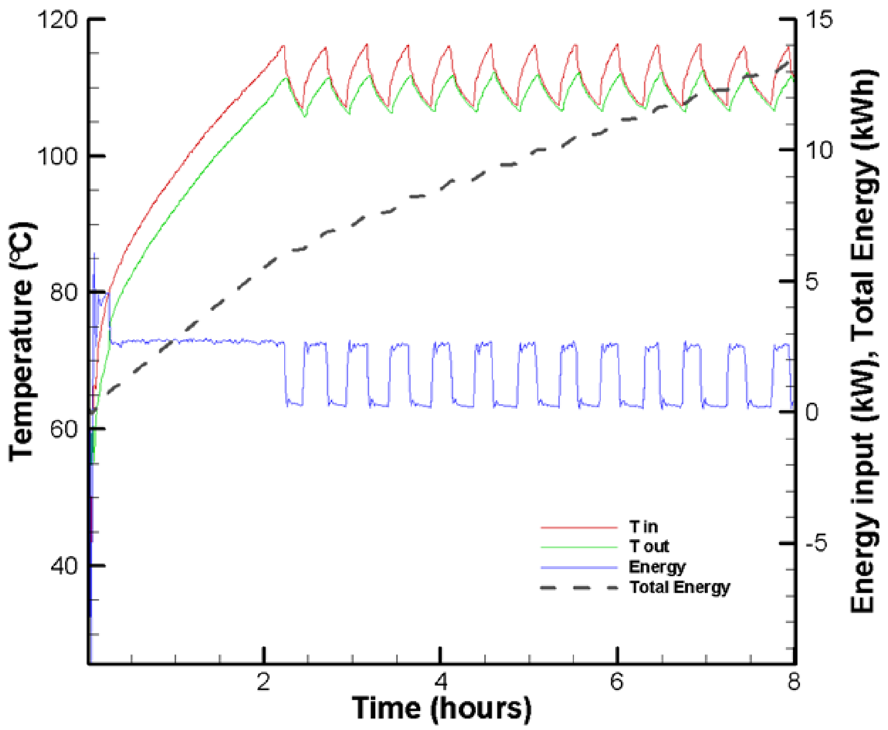

Figure 42: The measured minute-averaged inlet and outlet temperatures, calculated energy input rates and total energy transferred to the store for the first charging experiment.

A follow-on charging experiment was conducted after two days. This measured inlet and outlet temperatures and the calculated rates of energy input to the store based on the volume flow rate, properties of the heat transfer fluid. The measured temperatures are presented in Figure 43.

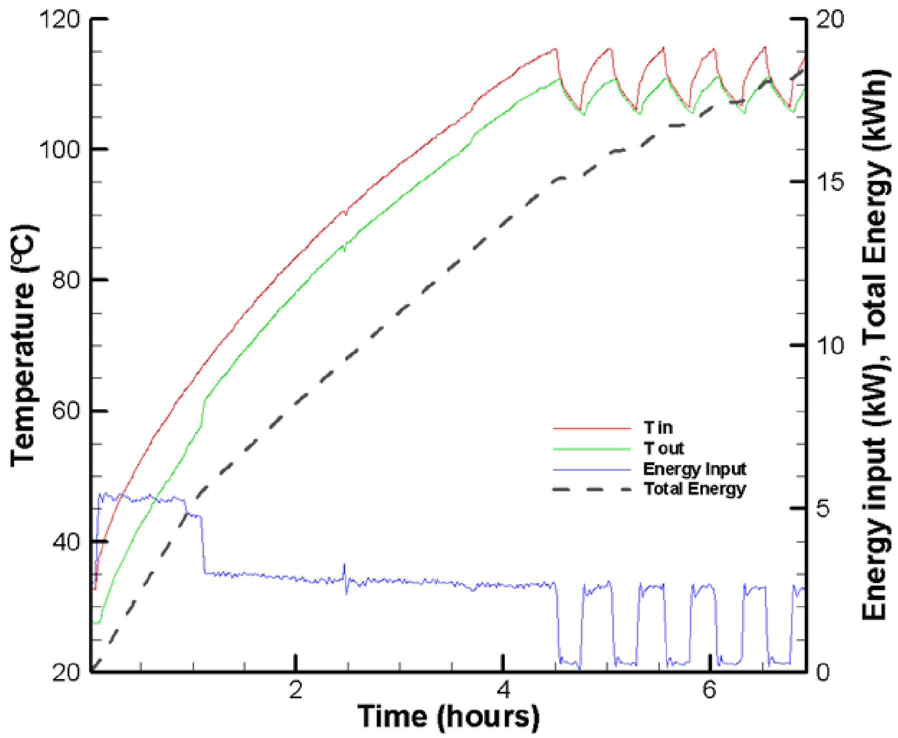

Figure 43: The measured inlet and outlet temperatures, calculated energy input rates and total energy transferred to the store for the follow-on charging experiment.

The energy input rates during the initial period of charging shown in Figure 42 and Figure 43 appear to be greater than the 3kW of heat supplied by the heater. This is not physically possible, with the discrepancy ascribed to an intermittent data logging anomaly previously identified. There is confidence that the true value would be slightly below 3kW, as observed for the following period. The heater was active for approximately 55% of the time resulting in an energy input rate to the stores of 1.65kWh per hour. The modified vacuum trap shown in Figure 44 enabled prolonged charging without intervention.

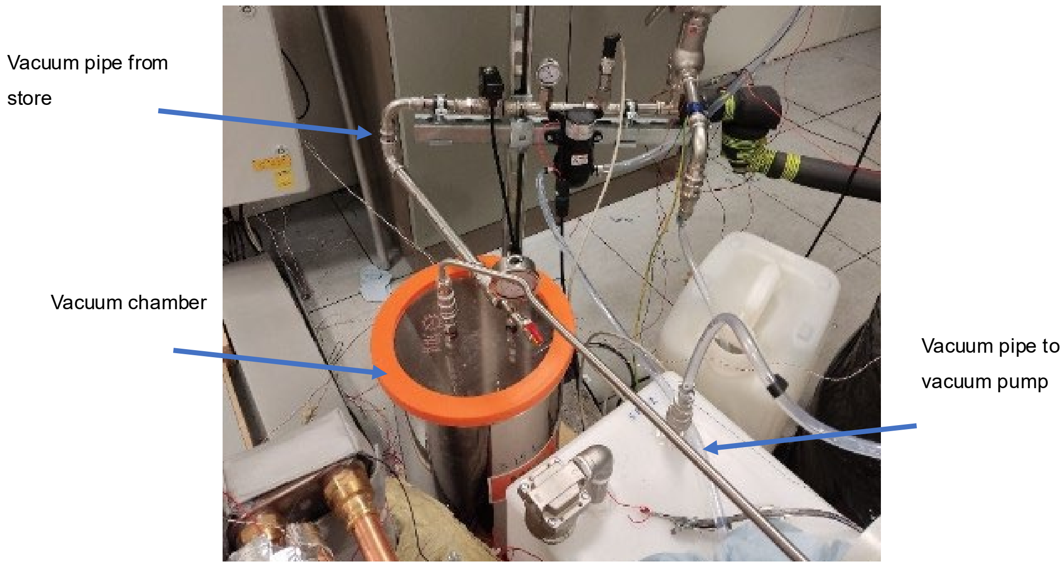

Figure 44: The modified vacuum pipe loop including a vacuum chamber condensation trap.

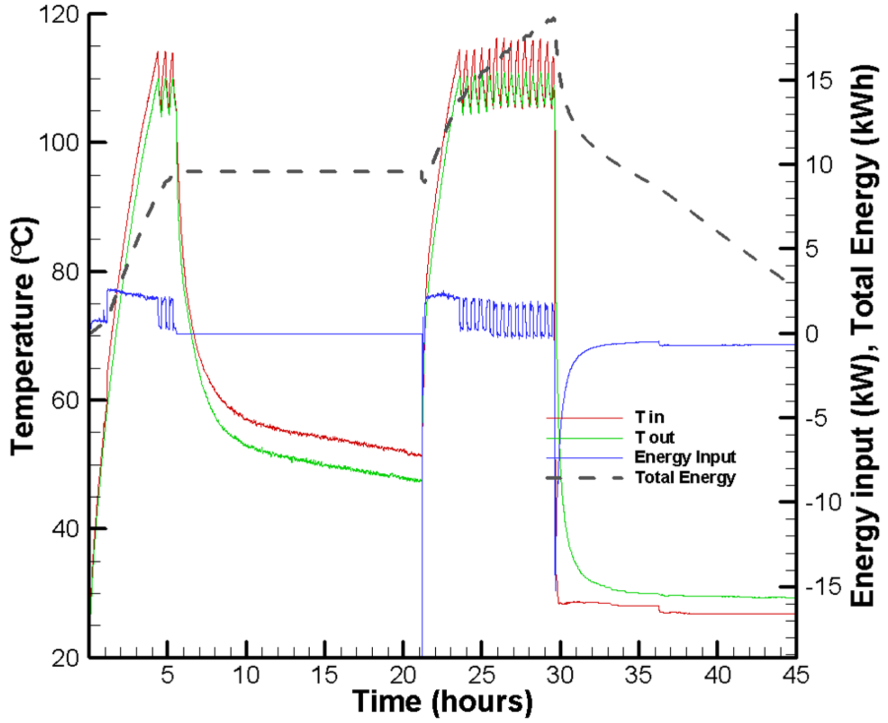

Figure 45: Measured inlet and outlet temperatures, calculated energy input rates and total energy transferred to the store for the first charging and discharging cycle.

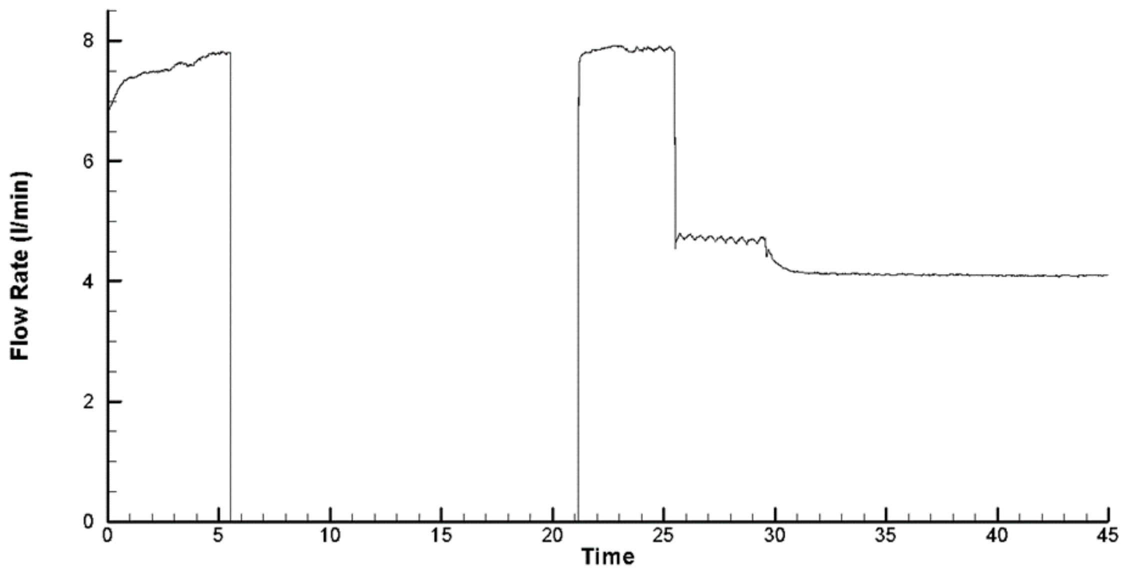

Figure 46**: Measured heat transfer fluid flow rates to the store for the first charging and discharging cycle.**

The measured inlet and outlet temperatures to the store, the calculated energy input rates to the store, and the total energy transferred to the store during the first experimental cycle are shown in Figure 45. The measured heat transfer fluid flow rates for the same experiment shown in Figure **46**. Key observations are listed below.

- Two charge cycles were conducted, from 0 to 5 hours and 21 to 28 hours.
- The flow rate during the first charge cycle was approximately 7.5l/min; the second charge cycle flow rate was 7.5l/min for the first four hours then reduced to 4.6l/min.
- Reducing the flow rate reduces pumping power requirements and changes the rate of heat transfer to/from the store. It also increases the temperature difference between inlet and outlet which will be beneficial for discharging.
- Between 5 and 21 hours there was no heat transfer fluid flow to the store, with temperatures measured on the inlet and outlet to the store decreasing during this time and maintaining a near constant temperature difference.
- Heat output rate during discharge is initially 15kW and rapidly reduces to approximately 1kW after two hours with 7kWh of heat discharged.
- The sensible heat component associated with raising the temperature of the store enclosure, TCS material, heat exchanger and working fluid from 20 to 100°C was calculated to be approximately 7.25kWh.
- In the subsequent four hours, a further 3kWh of heat is discharged; this is likely to be the result of moisture being redistributed within the store, leading to heat generation in the TCS material.
- The step change in the inlet fluid temperature shortly after 36 hours is thought to be the result of electrical noise on the data logging system.

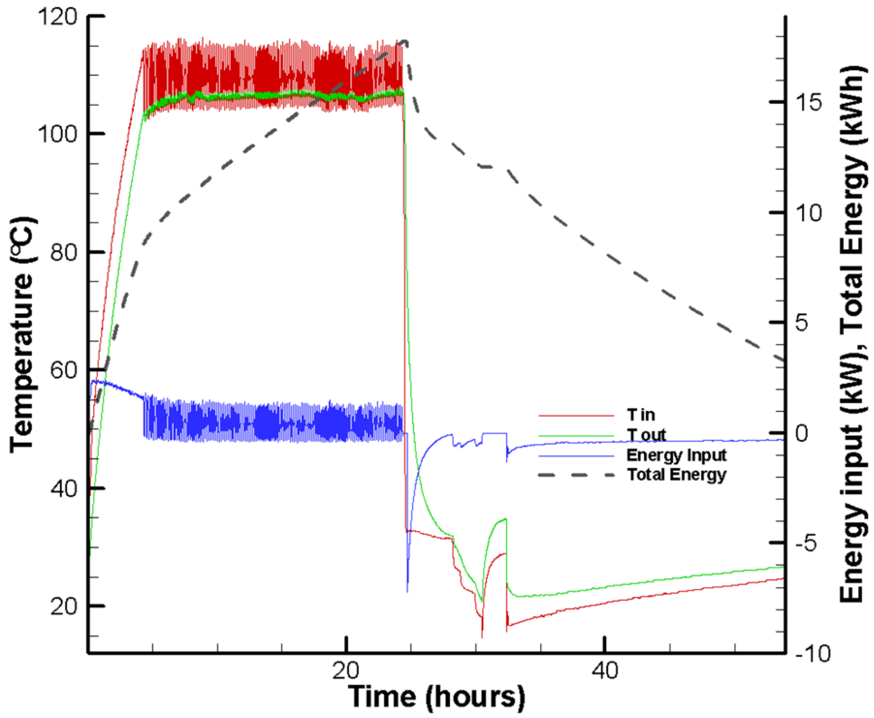

Figure 47: Measured inlet and outlet temperatures, calculated energy input rates and total energy transferred to the store for the second charging and discharging cycle.

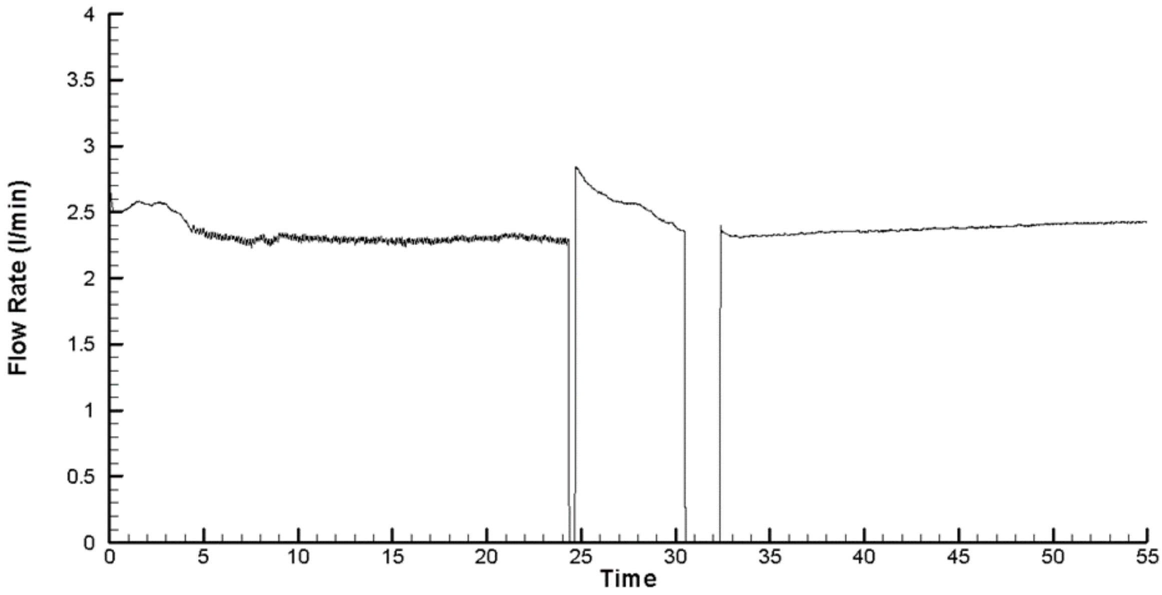

Figure 48: Measured heat transfer fluid flow rates to the store for the second charging and discharging cycle.

Results from the second cycle are shown in Figure 47 and Figure 48. This experiment used lower fluid flow rates (2.5l/min) over a 24 hour charging period.

- Lower flow velocity resulted in a more constant outlet temperature from the store after four hours when heater cycling commenced, more rapid on and off cycling of the heater, and a reduction in the rate of heat input to the store.
- After discharging, 10 litres of water was introduced into the store, and a further 8.75kWh of heat was extracted from the store.
- No temperature anomalies occurred in this experiment.

Based on measured temperatures and heat transfer fluid flow rates the energy charged to the store was 18kWh and 15kWh was discharged. This was the same for both the first and second cycles. In both cases even though discharging was not complete, 83% of the energy charged was recovered.

The storage capacity of the store comprises 7.25kWh of sensible heat and approximately 50kWh of thermochemical heat when fully charged. This indicates that the state of charge at 18kWh was 31% of the theoretical value. In both experiments the charge rate of the store did not reduce after the heater set point temperature was reached. This indicates that the store was able to be charged significantly further. Charging would require a minimum of 39 hours at the flow rate used in the first cycle.

Gen 2 Design and Manufacture

The Gen 1 stores were heavy and large with long charging times that would reduce the ability to charge the store at periods of low tariffs. Intermittent charging that simulated low tariff periods resulted in a low TCS heat storage to sensible heat input ratio. Heat loss is low for well insulated stores if charged on consecutive days. These observations led to the Gen 2 designs being of the same diameter and approximately half the height (0.99m). Table 3 presents comparative data for the stores. The specific heat capacity of aluminium is 900J/kg/K compared to approximately 500J/kg/K for stainless steel.

Table 3: Gen 1 and Gen 2 TCS store component masses and heat capacities.

System	Gen 1	Gen 2	Gen 2.1
Vessel mass (kg)	230	124	64
TCS material mass (kg)	188	90	91
HX Wet mass (kg)	37	18	18
Total sensible mass (kg)	267	142	82
Total mass (kg)	455	232	173.
TCS material / total mass (%)	41	39	53
Calculated total specific heat capacity (kWh/°C)	0.091	0.046	0.045

Gen 2 systems charge time was halved due to the lower sensible and thermochemical heat capacity, helping them to make better use of low electricity tariff periods. The Gen 2 stores used the same heat exchanger fin design, shown in Figure 49.

Figure 49: Gen 2.1 vessel, heat exchanger and TCS material.

Economic considerations

A cost analysis of various scenarios for a 10-year payback is presented in Table 4. Base case conditions and assumptions used for the calculations are:

- Annual interest rate on borrowed capital 5%
- Annual increase in electricity tariff 5%
- There was no additional maintenance cost, with the assumption being that a visual inspection would be performed annually when servicing other parts of the heating system.
- TCS thermal stores charged directly with heat produced by electrical resistance heating in order to achieve high temperatures (above what an ASHP would deliver).
- Round-trip efficiency charge to discharge assumed to be 0.8 to account for sensible heat losses from the store

Table 4: The calculated difference in electricity tariffs (in £) between charging and discharging of a TCS store per kWh of storage capacity to achieve breakeven in 10 years..

Cycles per Annum	1	5	10	50	100	200
Cost per kWh storage capacity £100.	£12.50	£2.50	£1.25	£0.25	£0.13	£0.06
Cost per kWh storage capacity £200.	£25.00	£5.00	£2.50	£0.50	£0.25	£0.13
Cost per kWh storage capacity £400.	£50.00	£10.00	£5.00	£1.00	£0.50	£0.25
Cost per kWh storage capacity £200. Interest rate on capital 6%. Annual increase in tariff difference 5%	£26.33	£5.27	£2.63	£0.53	£0.26	£0.13
Cost per kWh storage capacity £200. Interest rate on capital 7% Annual increase in tariff difference 5%	£27.69	£5.54	£2.77	£0.55	£0.28	£0.14
Cost per kWh storage capacity £200. Maintenance cost 3% of capacity cost increasing annually with interest rate.	£32.50	£6.50	£3.25	£0.65	£0.33	£0.16
Cost per kWh storage capacity £200. Comparison with ASHP with COP of 2.5	£62.50	£12.50	£6.25	£1.25	£0.63	£0.31

From Table 4 we can establish:

- For cost per kWh of storage capacity of 100 £/kWh, at least 50 cycles are required to achieve breakeven with a tariff difference between charging and discharging of £0.25.
- If compared to providing heat with a heat pump with a seasonal COP of 2.5 the tariff difference required would be £0.625.
- A large price differential between time of charging and discharging is needed to make low usage (annual discharge cycles) cost effective.
- 10kWh store that could be cycled more frequently would be more appropriate for domestic settings (adopted for the proposed Gen 3 design).

Outcomes: Gen 3 Design

The outcomes of the Gen 1 and Gen 2 manufacturing and testing packages, the findings from the installations at CEH, and the economic considerations summarised above were used to inform the design of a future Gen 3 TCS system. The primary aspects considered were appropriate sizing for domestic applications; and reducing the charge time by increasing heat transfer rates.

Due to the characteristics of domestic heat loads a 50kWh thermal store in a domestic setting is unlikely to be cycled frequently. A 10kWh store could be cycled more frequently although this would be dependent on suitable periods of low and high tariffs for electricity. Due to this the proposed design for a Gen 3 TCS system is based around a 10kWh storage capacity.

Heat transfer to and from the developed TCS system is strongly dependent on the temperature difference between the heat exchanger and the packed bed of TCS material; the surface area available for heat exchange; and operating pressures. For the Gen 1 and 2 stores, the charging temperature was limited to <110°C due to certification requirements. Addressing these requirements such that the store could be operated at the initially planned 140°C would substantially improve performance.

To increase the heat exchanger surface area within the Gen 1 and Gen 2 designs, fins were added to the heat exchange pipes in the current design. These increased the effective surface area by a factor of 2.5, from 0.0152m^2 to 0.3730m^2 per metre of pipe, and there is scope to further maximise this area in future iterations.

Finally, for the Gen 1 and 2 stores, the pressure in the store was reduced during charging to more effectively remove water that is driven off from the packed bed. However, the trade-off for operating at sub-atmospheric pressures is that both conductive heat transfer from the heat exchanger to the bed, and conductive and convective heat transfer within the bed are reduced. For future designs there is potential to improve heat transfer rates through more refined pressure control, with charging generally being conducted at atmospheric pressure or above and vacuum pressure applied as needed to intermittently remove water vapour.

Proposed Gen 3 TCS system design

A schematic of the proposed Gen 3 TCS system is presented in Figure 50. Key features:

- 10kWh store capacity to capitalise on cost effectiveness of shorter-term storage being operated at greater than 10 cycles a year.
- Storage material weight 40kg.
- Increased heat transfer to enable rapid charging and discharging; this also enables sensible heat to be utilised, improving round trip efficiency.
- Smaller internal diameter of 0.22m to ease installation; height of store enclosure 1.7m, with a flange and removable top to allow filling with TCS material on site.
- Pressure certification, enabling use of significantly lighter 1.6mm stainless steel (similar to domestic hot water cylinders rated to 6 bar). Lighter materials reduce cost and also the fraction of heat stored as sensible heat within the store.

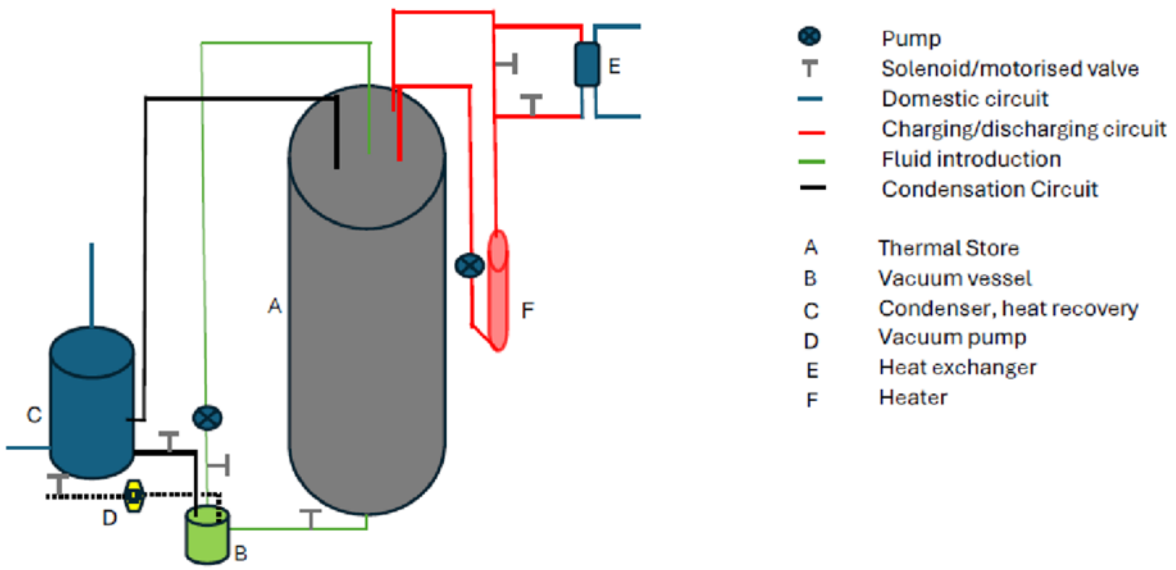

Figure 50: Schematic of the proposed Gen 3 TCS system.

Heat Exchanger Design for a 10kWh TCS store

The store heat exchanger design consists of a double ring heat exchanger with an enhanced fin design to increase the heat exchange surface area. The heat exchange surface area per metre length of pipe is 0.287m^2. The ratio of heat transfer area in the new proposed heat exchanger to the old heat exchanger per kg of TCS material is approximately 1.92:1. Pipe centres are 44mm apart

Heat transfer performance will be increased by operating the store at pressures greater than atmospheric and employing higher temperatures for charging. We anticipate 0.9 bar during the initial stages of the charging would be sufficient. The vacuum pump would only operate for the initial period of charging.

Charging/Discharging Circuit

To reduce head loss due to friction, piping length within the store was halved. The heat exchanger would be divided into parallel flow paths, further reducing head losses.

An oil-based heating circuit that meets health and safety requirements for use in a domestic environment is proposed, providing input temperatures up to 140°C with a heat power input of up to 3kW. The lower heat input rate is more suited to domestic power supplies and would reduce low voltage network loads, making the anticipated issues from increased loads resulting from electrification of heat and transport more manageable.

Cost reductions expected

Significant cost reductions can be achieved by reducing the material content of the thermal store enclosure, simplifying the heating (charging/discharging) system and mass production. Target maximum costs for components are:

- Pressure vessel regulations-compliant stainless steel enclosure £400.
- Oil pump and oil heating system £400.
- Heat exchanger £600.
- Vacuum system and water delivery system £400.
- TCS material £400.
- Manufacture and assembly £500.

If mass production brought this cost down from £2,700, to below £2,000, then TCS systems might be viable for heat storage applications with 100-200 cycles a year.

Suggested applications for larger scale TCS systems

Challenges for use in domestic environments:

- The high temperatures needed to charge the TCS store are provided by direct electrical heating (maximum COP of one). This compares unfavourably with other store types that can be charged at a lower temperature using an ASHP (COP of ~2.5).
- Regulatory challenges from the use of oil heat transfer fluid at high temperatures and pressurised stores.

The TCS may be more suited to other non-domestic storage applications that capture waste heat at temperatures from 120°C to 150°C. Two application scenarios might be:

- **Industrial batch processes.** Enabling process energy and cost efficiency to be improved by capture, storage and utilisation of heat with many charge-discharge cycles a year.
- **Capture and transport.** Capture and store heat in a TCS capsule that can be transported by lorry or similar and kept for later use or to meet a remote heat demand.

Creative Energy Homes (CEH)

Work at CEH was broadly aligned with that for the PCM stores, aiming to understand TCS store performance in realistic environments. TCS stores were installed within one dwelling and the CEH district heating network (DHN).

Both a Gen 1 and Gen 2 were physically installed in the domestic dwelling , with a decision being made to prioritise testing of the smaller-scale (and thus more domestically appropriate) Gen 2 store. This unit was integrated such that it could supply heat from the TCS store directly to the home heating circuits. The trial sites presented significant space constraints, involving installation of the ancillary rig, control equipment and the storage unit itself into restricted, areas of the property archetypes. The design and deployment provided valuable learning.

Technical outputs

TCS Gen 1 testing

The Gen 1 TCS units installed (Figure 51 and Figure 52) can deliver up to 50kWh of energy. The weight and height of the unit presented safe moving and handling challenges. Unlike a laboratory, the areas around the homes have slopes, kerbs, undulating surfaces and obstacles. Delivery positioning was carried out by a contractor specialising in heavy item movement before University of Nottingham technicians completed the installation. Geberit Mapress tools and fittings were used.

Figure 51: Completed installation of the Gen 1 store into the DHN shed, prior to insulation.

A panel heater was installed into the shed to provide frost protection during the winter months. All electrical consumption data associated with the ancillary rig operation was collected. Light and space heater consumption was omitted as they do not form part of the core installed system; usage was also low.

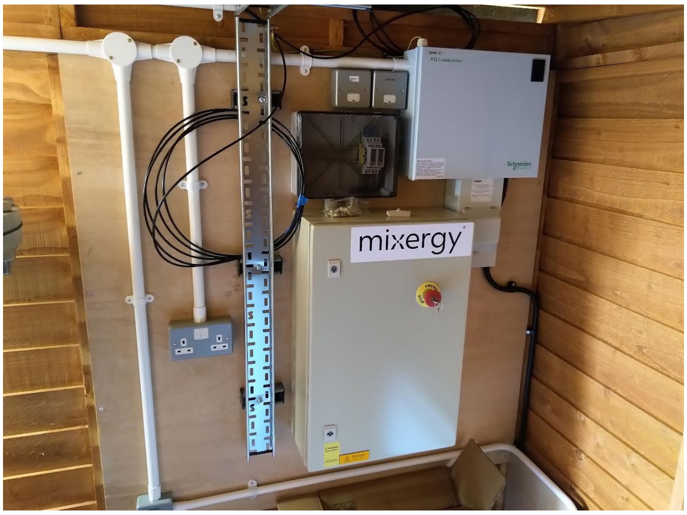

Figure 52: Electrical provision in external shed of the dwelling.

A charging cycle for the store linked to the DHN is presented in Figure 53 to Figure 55. Figure 53 illustrates the controlled charging of the TCS store over a period of approximately six hours. The ancillary rig developed to charge the store featured a 3-stage electric heater, capable of providing 3kW, 6kW and 9kW outputs. Figure 53 illustrates the mechanical control applied to the heating element to prevent exceedance of the specified maximum circuit temperature; thermal output is initially “pulsed” at 9kW output, before being stepped down to 6kW and ultimately 3kW outputs. The operating temperature is then maintained using the 3kW power stage.

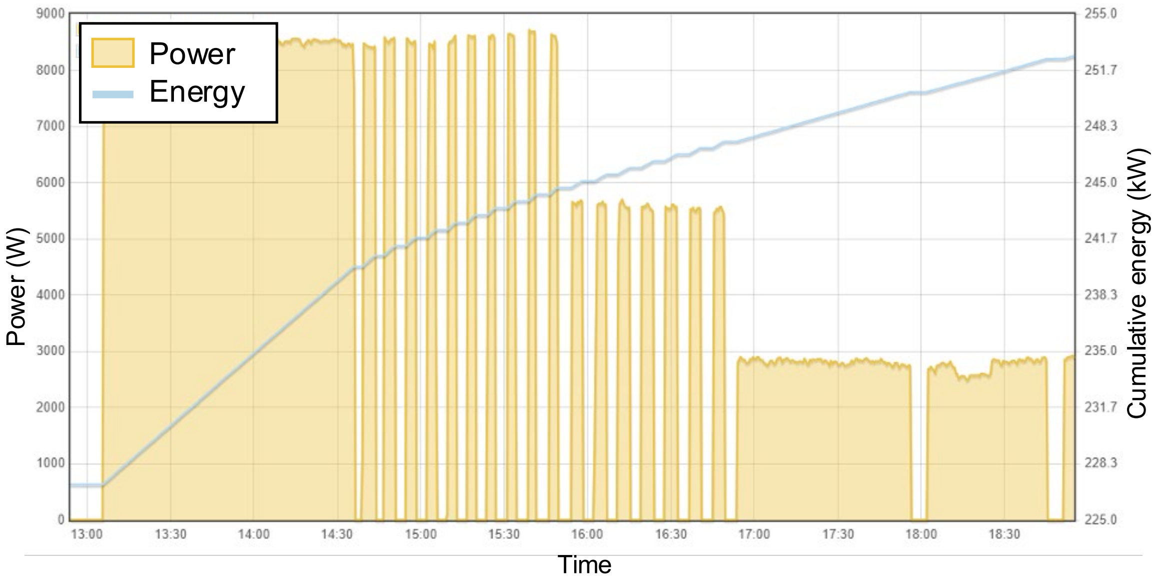

Figure 53: Charging of TCS unit in DHN at up to 9kW power input.

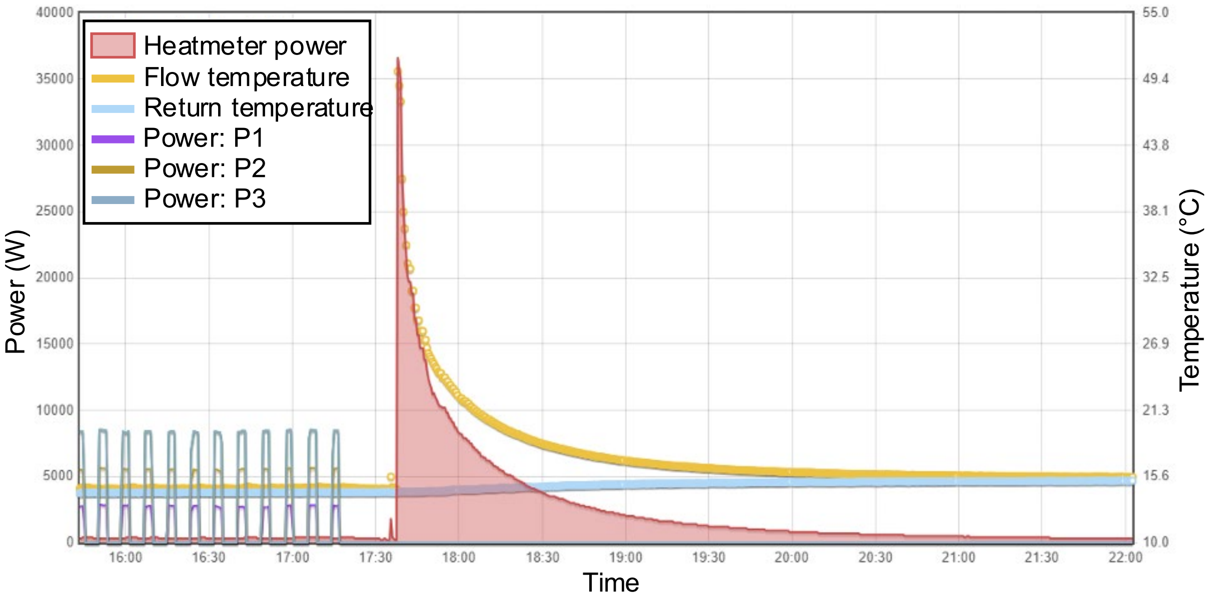

Figure 54: Conclusion of charging period and reutilisation of sensible heat through discharge to DHN main buffer tank. The flow/return temperatures and instantaneous power values relate to the heat meter installed on the DHN buffer tank. The values labelled P1 to P3 indicate the electric input to each heating element within the ancillary rig.

Figure 54 illustrates the conclusion of a TCS charging period, with the stop condition reached at around 5.30pm on 17/01/25. At the conclusion of charging, a substantial quantity of sensible heat is retained within the fluid of the charging circuit. The system is set up such that this may be utilised through discharge to the DHN hot water buffer tank. This discharge process may be observed from around 17:40 in Figure 54, which was captured on 17th January 2025.

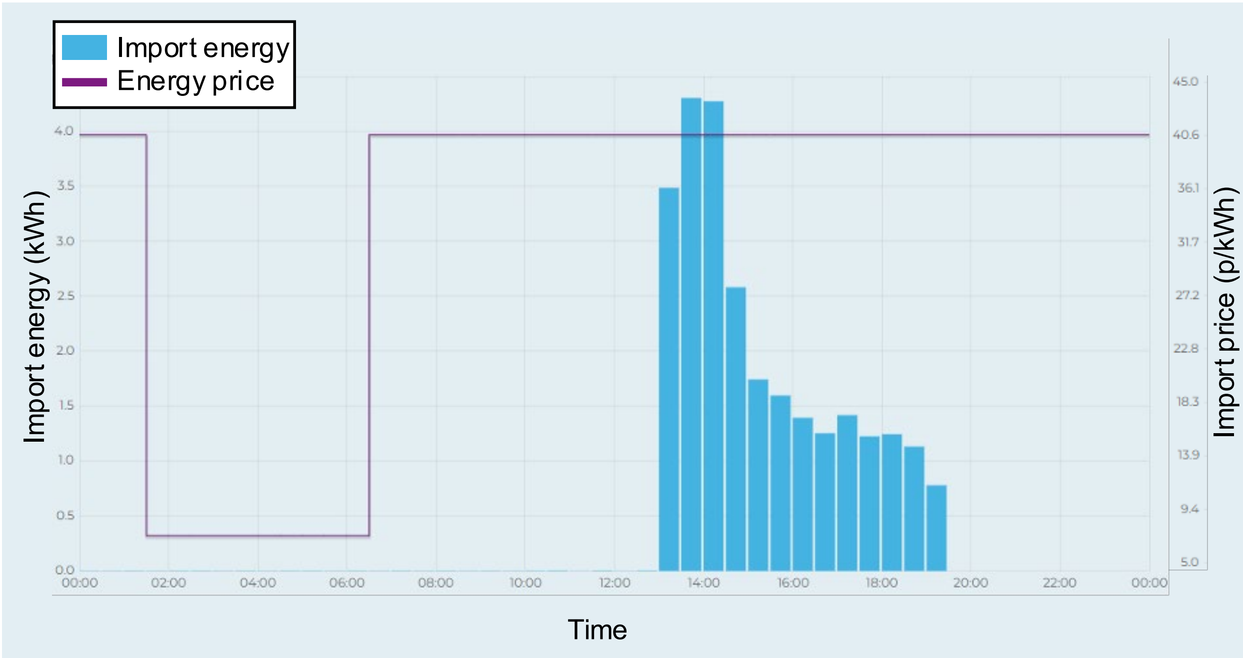

Figure 55: TCS charging period on 22nd January 2025. The energy import profile for the approximately 26 kWh of electricity used to charge the TCS store is shown in blue. The Octopus Go tariff, including the 5-hour off-peak period, is shown in purple.

Figure 55 provides an initial indication of the length of the Gen 1 TCS charging period and how it relates to the overnight off-peak charging period provided by the Octopus Go tariff, which may be a candidate TOUT for the TCS devices. As can be observed, the charging period for the Gen 1 unit exceeded the 5-hour off-peak period offered by this tariff, and thus a portion of charging process would have occurred at the “standard” tariff rate. Whilst very preliminary, this is consistent with the design approach taken for the Gen 2 unit. By approximately halving the energy input required to reach full charge, there is potential for charging to be timed to fit primarily within the Octopus Go 5-hour off-peak period. It is noted that the 9kW power demand may present a challenge if overnight EV charging is also required. Homes with a 100 Amp fuse may have sufficient capacity to provide for the combined power requirement if no other high draw equipment is operational in the household overnight. Alternatively, holistic control and optimisation of the technologies would be expected to provide a more robust approach.

TCS Gen 2 units

Figure 56: Completed TCS Gen 2 system at the dwelling.

Figure 56 shows the interior of the shed attached to the dwelling at the conclusion of the project. The insulated Gen 2 store is shown on the right-hand side towards the rear of the store, with the larger Gen 1 store being positioned to the left of the image (slightly obscured). A great deal was learnt from the physical installation of the Gen 1 store, but the decision was taken to prioritise testing on the domestically focused Gen 2 store. The Gen 1 installation had occurred before the final set of design modifications had been identified and implemented at CREST. Implementing these modifications at CEH would have required access to the underside of the Gen 1 TCS. This would in turn have required the TCS to be lifted out and removed from the shed, which was deemed costly and impractical.

At the end of February 2025, the TCS Gen 2 system was completed and began its first discharge by introducing deionised water to the dry TCS material. A partial discharge was undertaken. The system was actively discharging (water was being pumped into the TCS tank) for six minutes from 12:43 to 12:49 as seen in Figure 57. During this period a maximum recorded temperature increase of 20°C was measured, peaking at 34°C. Heat is still produced after the charging pump has been turned off due to the already introduced water infiltrating throughout the TCS material, peaking at 40°C. At 14:09, heat was dumped from the TCS system into the home heating system hence a 10 to 15°C drop in circuit temperature.

Approximately 1.17kWh of energy was released from the Gen 2 TCS in the partial discharge as seen in Figure 58. To achieve the estimated energy storage capacity of 25kWh for a Gen 2 TCS tank, the system would need to discharge for 250 minutes.

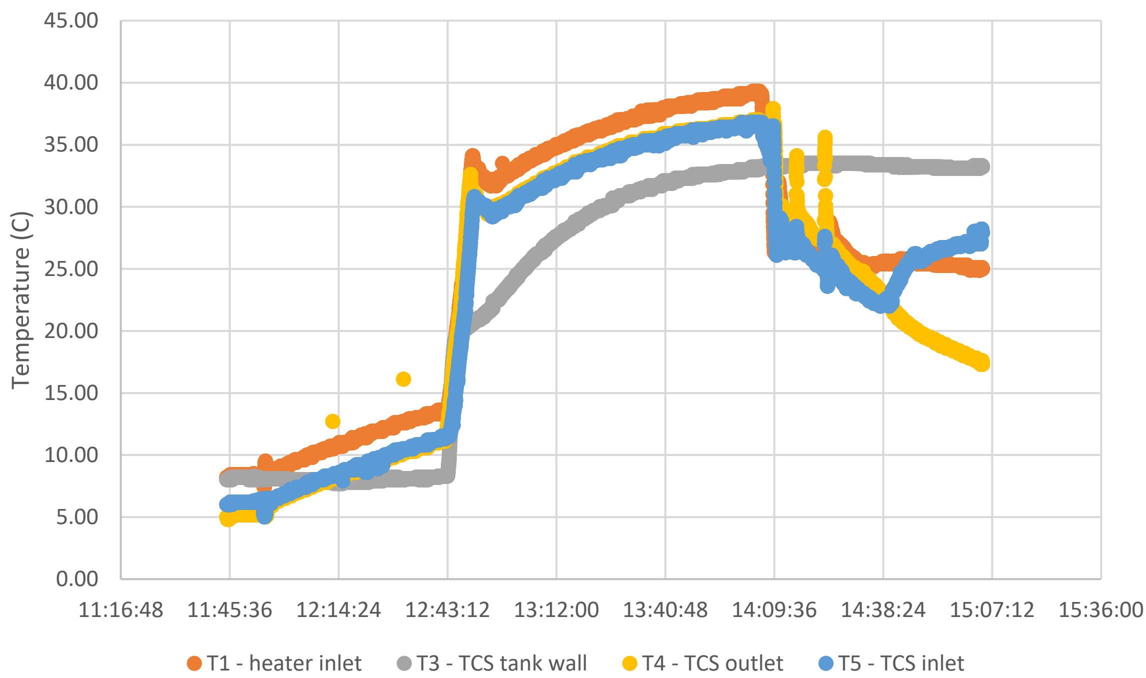

Figure 57: First discharge temperatures of Gen 2 TCS system at the dwelling.

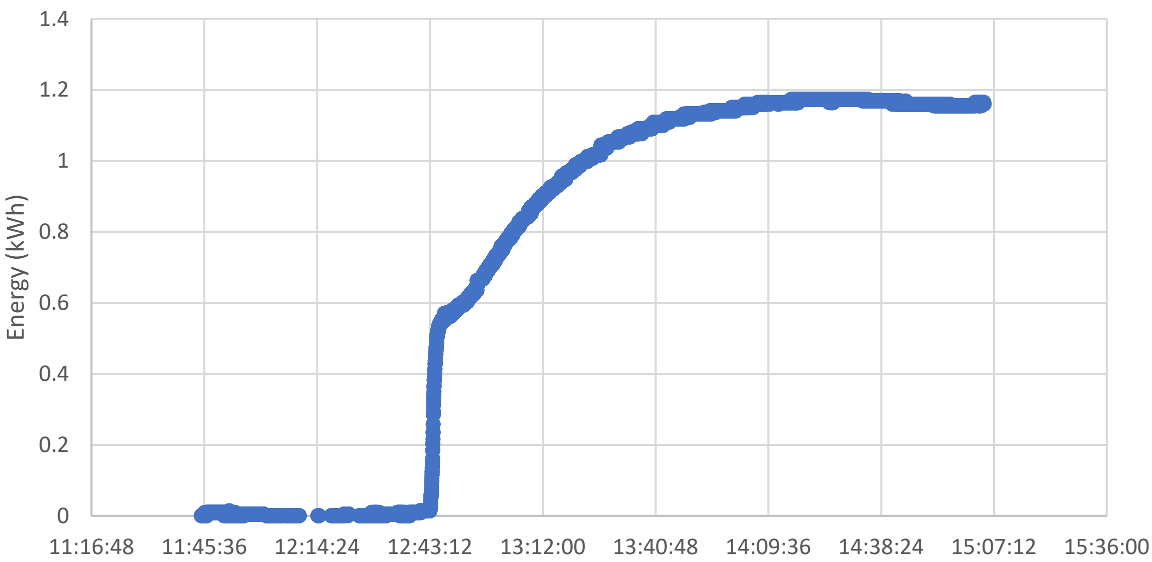

Figure 58: Energy produced by Gen 2 TCS at first partial discharge.

Outcomes

The work carried out in installing and operating the TCS Gen 1 and Gen 2 systems achieved demonstration of both generations of this first of a kind technology in a realistic domestic environment, representing a substantial achievement.

The real settings provided valuable lessons learnt, particularly in relation to the installation process which include:

- Gen 1 units took a substantial period of time to fully charge.
- When discharging, a large amount of energy is released over a short period which is inappropriate for a domestic setting.

We concluded that the Gen 1 units were not well-suited for domestic use, but present opportunities for adoption at larger scale within district heat network or commercial/industrial settings.

- The smaller Gen 2 store takes the equivalent space of a standard item of white goods, is lighter and more manoeuvrable. This demonstrated the potential for a simpler, more cost effective and space efficient store, whilst acknowledging that competing technologies (notably hot water tanks) are still much more straightforward to install.
- The smaller Gen 2 TCS store requires shorter timeframes to charge and dry the TCS tank, making it better sized for a domestic setting.
- Further work is required to develop a discharge procedure or control code to provide sufficient heat on demand, without overheating the home.
-

Laboratory for Verification and Validation (LVV)

This section outlines the work that has been undertaken by the University of Sheffield at the Laboratory for Verification and Validation (LVV) on the demonstration and characterisation testing of a Gen 1 thermochemical storage (TCS) unit developed by Loughborough University. The design and testing principles are documented by Loughborough University in earlier sections of this report. However, due to the bespoke nature of the installations for these early-stage systems there are some minor differences in both the setup of the TCS itself and in the operational procedure adopted.

The Gen 1 TCS unit was tested in ambient conditions in the LVV and is set up in such a way that it would be possible to extend the testing in future to consider other environmental conditions. As the material within the Gen 1 TCS unit was in a partially dry condition (i.e., charged) when it was first integrated into the test rig proposed in LVV, an initial discharge of the unit was carried out to enable quantification of recoverable energy from this initial state. Following this, a full charge followed by a full discharge was conducted. The work completed builds the understanding of the operation of the unit and provides useful initial data on the storage capacity of the unit showing the charge and discharge power profiles. The outcomes of this work provide independent validation of the performance of the system in laboratory conditions and help inform the future direction of research on the operation of the TCS system, both in laboratory and practical implementations.

Technical outputs

Figure 59: The full test rig set-up for TCS testing

A test rig was developed to allow controlled charging and discharging cycles of the TCS unit to be performed, thus allowing detailed performance characterisation. The rig is shown in Figure

59, with a schematic representation of the test setup including key temperature sensor locations shown in Figure 60.

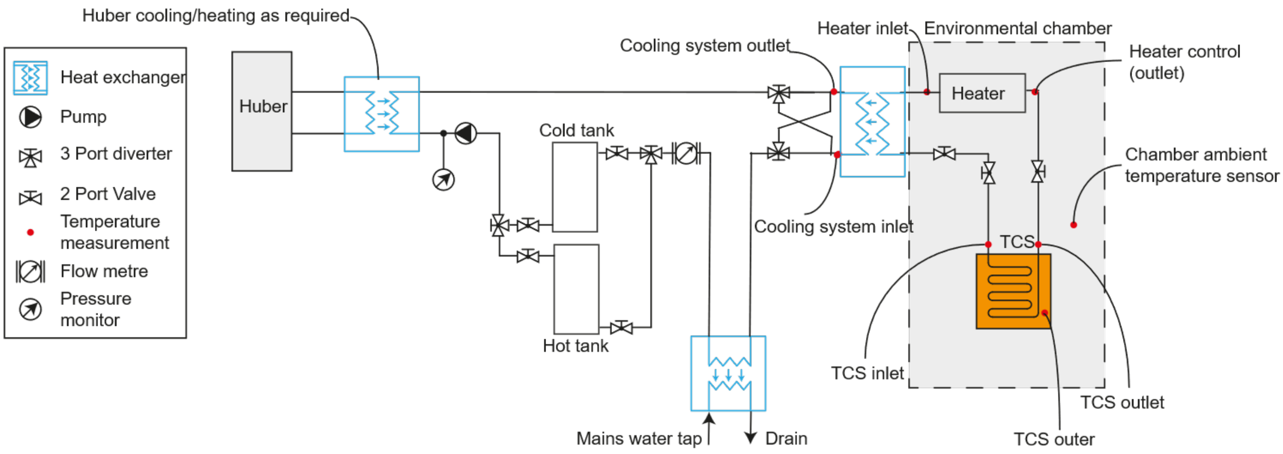

Figure 60: Schematic representation of the TCS test setup.

The test rig comprises two integrated systems to allow both charging and discharging operations. The system located outside the chamber was based on the rig used for the characterisation of the phase change material (PCM) storage units in LVV, as described in the LVV PCM testing section. This cooling system was used to allow effective discharge of TCS by providing cool water at a constant temperature of around 20°C. An adaptation was made to this cooling circuit operation, where an additional heat exchanger (supplied by cold mains water) was used to extract heat from the water coming from the charged TCS unit. The remaining cooling was controlled by the Huber Unistat 510, as was the case with the PCM testing (see LVV PCM testing section).

The Gen 1 TCS unit, located inside the environmental chamber as shown in Figure 61, was integrated into the cooling system. Hydration and dehydration of the TCS material (i.e., discharging and charging, respectively) was achieved using the ancillary system developed by Loughborough University and the controller developed by Mixergy. The key elements of the system include the 9kW heater that was used to generate the hot, dry air used for charging, and the tank used to store the fluid introduced into the TCS system during the discharging process. The TCS unit was insulated to avoid excessive heat loss to the environment.

The installed pumps, valves and heaters were controlled by the Mixergy controller connected to a computer. Two data acquisition systems were used to record the data during charging/discharging tests. The first is the built-in system in the Mixergy control, collecting temperatures, pressures, flow rate and relay control changes in the TCS system located in the chamber. This was used for observing charging metrics (i.e., power and cumulative energy), real-time monitoring and controlling the system. The other data acquisition system is the LVV setup, including temperature sensors and flow rate metering within the cooling system to allow both observation of the temperatures and calculation of discharge powers and energies.

Figure 61: The TCS unit, including ancillary equipment, located within the environmental chamber.

Initial discharge of the Gen 1 TCS unit

As the Gen 1 TCS unit was partially charged when it was integrated into the testing rig, an initial discharge experiment was performed. The discharging process required provision of fluid into the system. The fluid injections were performed as a series of short bursts rather than as a single step, following the test protocol recommended by Loughborough. Each fluid injection period was stopped once it was observed that the injected fluid was being exhausted from the TCS system. The discharging process was ended once the temperature difference between the inlet and outlet of the cooling system was smaller than 2°C.

Figure 62 shows the raw temperature data across the system collected during several hours of discharging. The discharging power and the cumulative energy discharged from the system can be seen from Figure 63.

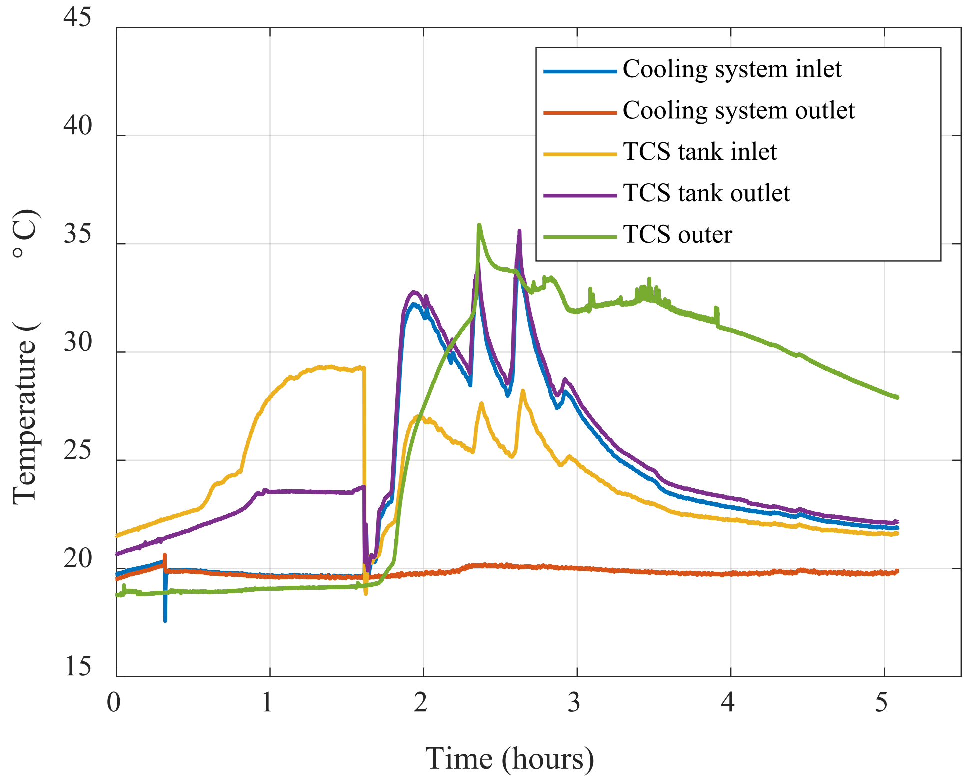

Figure 62: Temperature data during initial discharge of Gen 1 TCS unit. Temperature sensor locations are shown in Figure 60.

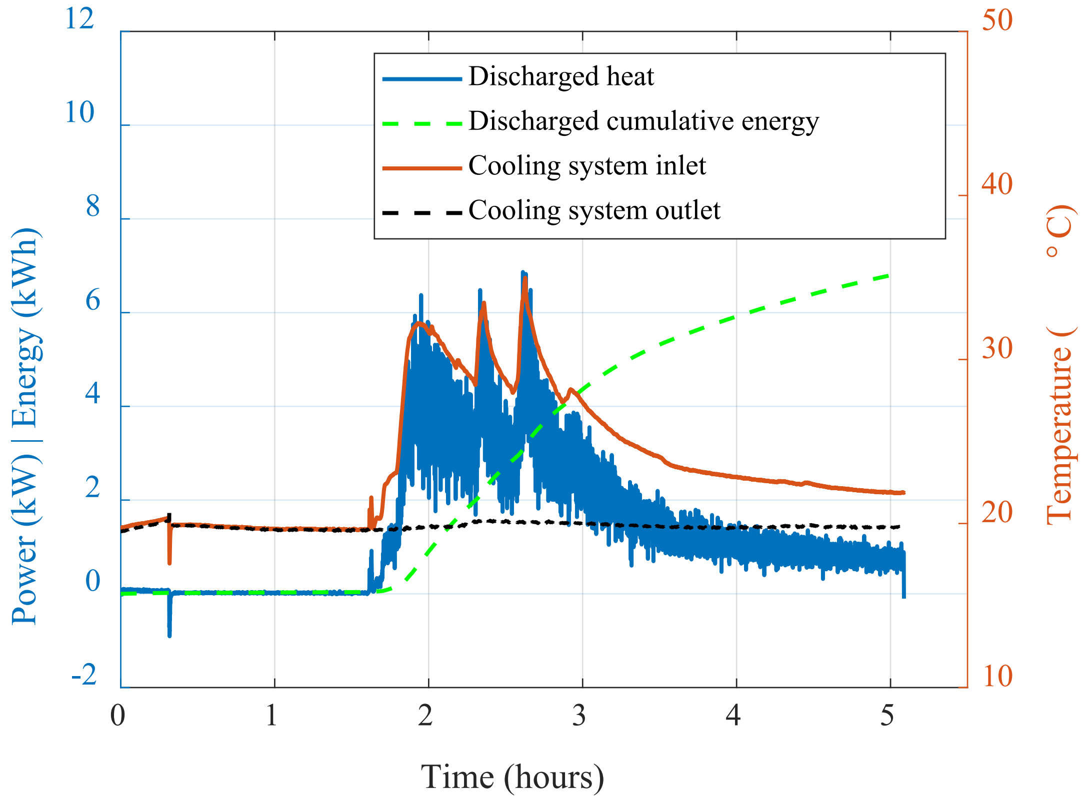

Figure 63: Derived power output during initial discharge of Gen 1 TCS unit

It can be seen from Figure 62 and Figure 63 that cooling water at approximately 20°C was constantly provided into the cooling loop of the system to allow effective discharging of the energy from the TCS unit. The returning temperature to the cooling system (i.e. cooling inlet) reached a peak value of about 35°C in this initial discharge. The drops in the outlet temperature were caused by the subsequent injections of fluid into the TCS system. The heat power discharged from the TCS unit peaked at around 6kW and showed a consistent power flow above 2kW for more than 1 hour. The relatively noisy data in the heat power was attributed to fluctuations in the flow rate of the cooling circuit. Despite being set to a nominal value of 5l/m (note that this was different from the flow rate within the TCS system which was set to 12l/m), the measured flow rate fluctuated between about 3.5l/m and 7l/m. It can be seen from the cumulative energy discharged that about 7kWh of energy was extracted from the partially discharged Gen 1 TCS unit.

Charge and discharge cycle test of the Gen 1 TCS unit

After the initial discharge, a successful charging/discharging cycle was performed for the Gen 1 TCS unit, lasting over 100 hours. Figure 64 shows the overall temperature variations at key locations during this test period. The plot shows that there were two charging periods, an idle period and finally a discharge period.

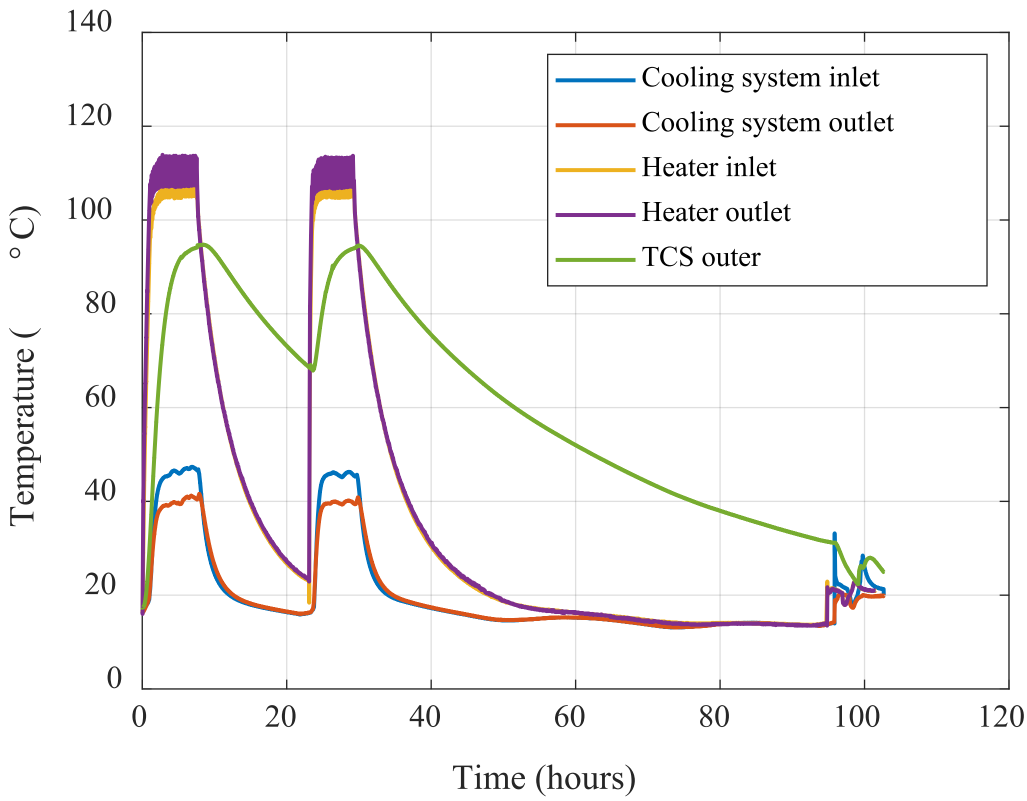

Figure 64: Temperature data during a charge/discharge cycle test of the Gen 1 TCS unit

The charging phase of the test period required the heaters to be run to provide the heat required to remove the fluid from the TCS material within the store, given that the store was in a discharged state at the beginning of the test. Figure 65 shows the related data for this charging phase. During the two charging phases, 3 to 5kW of heat was provided to the system with a heater hysteresis between 105 to 110°C. This resulted in a cumulative charging energy of around 47kWh being generated by the heater, with a substantial portion of this heat being used to raise the sensible heat of the store and a further portion contributing to dehydration of the TCS material. Even though a sufficient level of charging energy was provided to the TCS system, the amount of fluid removed from the TCS system was lower than expected, and significantly smaller than that which had been introduced during the initial discharge. This was attributed to the physical design of the pipework which is used to remove the fluid collecting within the tank as the required heat is introduced to the system. As a result, it was considered that the majority of the energy provided to the TCS system during the charging phase contributed to raising/maintaining the sensible heat within the thermal mass of the system, rather than the dehydration process. As a result, there was an expectation that the amount of energy that may be recovered from the TCS system would be substantially smaller than that used for charging.

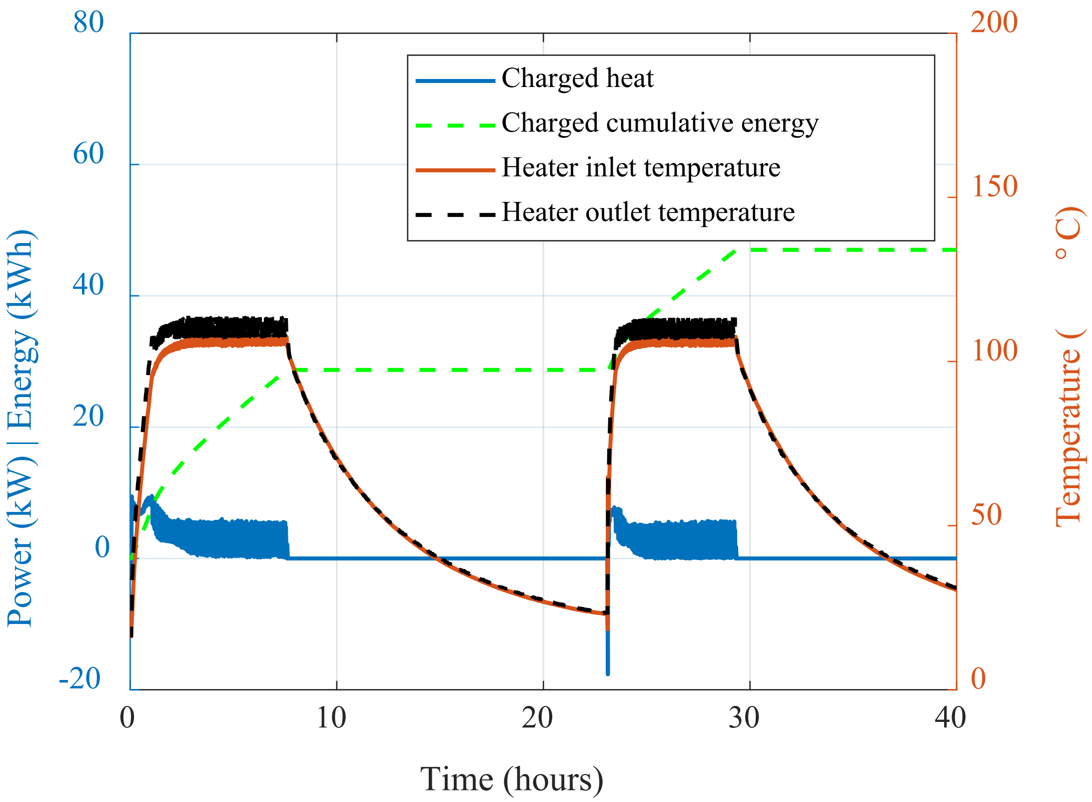

Figure 65: Derived powers and cumulative charging energies during the charging phase of the charge/discharge cycle test of the Gen 1 TCS unit.

As was the case for the initial discharge test, the discharging phase of the cycle required provision of fluid into the active material within the TCS store. The same process was followed, with fluid injection being stopped once the TCS unit began to exhaust the injected fluid. The discharging process was ended once the temperature difference between the inlet and outlet of the cooling system was smaller than 2°C.

Figure 66 demonstrates the discharging behaviour of the system. Similar characteristics were observed to those seen in the initial discharge tests. During the discharging phase, cooling water at about 20°C was constantly provided into the system to allow effective discharging.

The return temperature of the cooling system reached about 28°C – note that this is smaller than the initial discharge as the system did not exhaust the expected amount of fluid in the charging phase. The discharging power peaked at around 3.5kW and it stayed above 1kW for over 3 hours. In total, despite the low level of removed fluid, over 4kWh discharging energy was achieved in the discharging phase of the Gen 1 TCS unit.

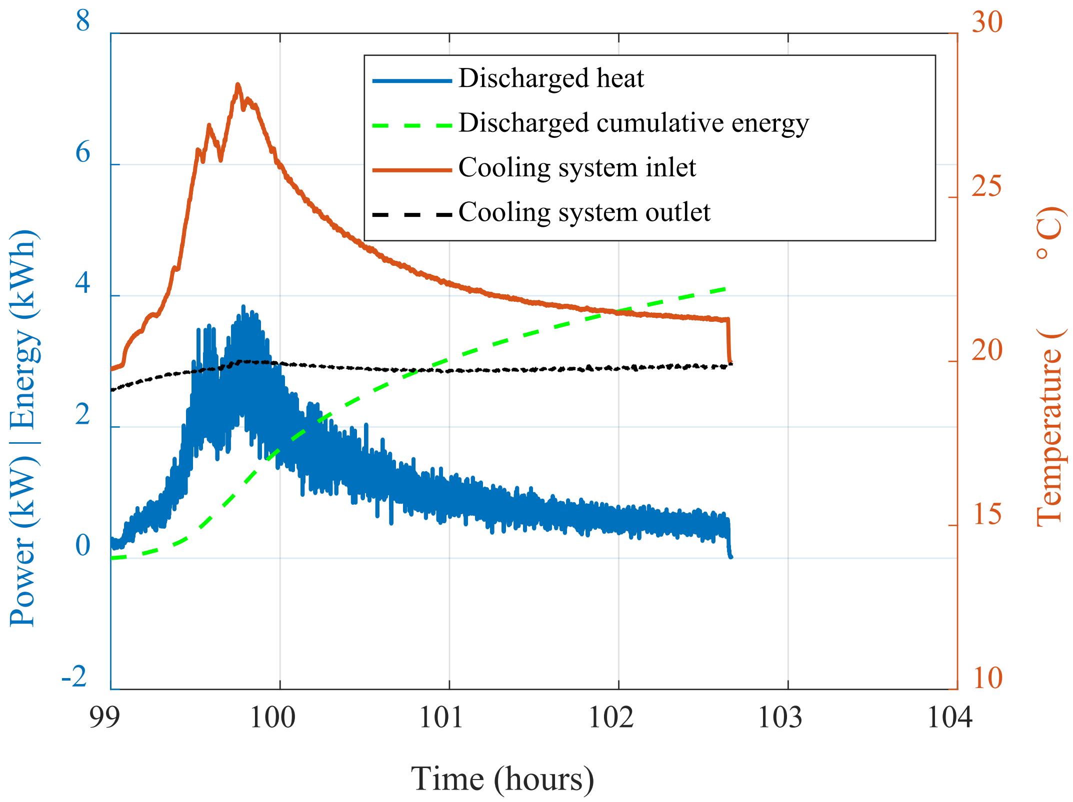

Figure 66: Derived powers and cumulative charging energies during the discharging phase of the charge/discharge cycle test of the Gen 1 TCS unit.

Outcomes

The work conducted at the LVV has successfully provided an independent testing set to validate the outcomes observed from initial testing at CREST. A great deal was learnt during the installation and initial operation of the system. As an example, one area of development was in adaptation of the hysteresis control loop applied to the heating circuit, implemented in concert with Mixergy. This allowed the ancillary system to deliver temperatures in a tight band (2 to 3°C) below the 110°C limit specified by PSSR regulations, whilst ensuring this limit was not breached. This was viewed as a valuable step forward in the operation of the system given the limited headroom between the evaporation temperature of the water and the limit specified under PSSR.

Following the initial test and the full charging/discharging cycle of the Gen 1 TCS unit in LVV, it was noted that there is scope for the TCS system to benefit from a significant amount of further research, development and optimisation. It was learnt from the tests that further modifications or arrangements were required for a more effective charging/discharging cycle. As an example, it was observed that alterations to piping layout would allow more effective removal of fluid from the TCS system during the charging phase, substantially improving round trip efficiency. It is believed that the TCS behaviours observed and the key learning points will be of benefit in the ongoing development of the TCS systems for long-duration heat storage applications.

The available testing window did not permit exploration of extended standing periods between charge and discharge. It would have been beneficial to conduct these in order to definitively demonstrate the major expected benefit of TCS as a storage technology, which is the expectation of zero standing losses for the thermochemical component of the stored energy. It would also have been beneficial to test the unit in a set of controlled environmental conditions as enabled by the testing chambers at the LVV. This would provide useful understanding for the assessment of the performance of the unit in a range of realistic conditions, with an example of particular relevance being emulation of the unit being situated in an external environment. Finally, it would have been beneficial to conduct comparable testing for the Gen 2 TCS unit, with an expectation that the lower thermal mass of the Gen 2 units will enable a significantly greater proportion of the charging energy to contribute to dehydration of the active material.

Lessons learned

- **Form factor**. A smaller size and weight of store would be required for domestic operation, with a high cycle rate required to make the stores commercially viable.
- **Pressure vessels regulations.** An optimised, fully certified vessel would reduce production costs, reduce system mass, and allow for higher charging temperatures. This would in turn improve both charge rates and round-trip efficiency.
- **Manufacture of heat exchangers.** Lab based manufacture of heat exchangers was time consuming and would be optimised if adopted at scale. Adopting brazed fittings would allow for higher operational temperatures and pressures, improving system performance.
- **Heat source for charging stores is not ready for domestic use.** There is scope for significant enhancement to scale down the system and integrate it with the store.
- **TCS installation was a complex task, particularly for the domestic trial site.** This contributed to the conclusion that the TCS system is better suited for district heating rather than single-dwelling applications.
- **The sensible heat present in the TCS system following charging may be recovered and utilised.** Doing so would substantially improve overall round-trip efficiency by maximising useful output from the high-grade heat used for charging.
- **Long charging periods are required for current storage designs**. It was found that charging using the 9kW electrical supply available in the DHN installation rapidly raised

the temperature of the store to initiate charging to begin. However, it took a long time for the main vessel to reach a uniform temperature, leading to long charging periods.

- **Difficulty in confirming “charged” status.** There is no validated method to evaluate whether the store has been returned to a dry state. In the laboratory tests, measuring the mass of water injected into and recovered from the vessel worked effectively for this purpose. However, it did not prove possible to recover all of the input water at the CEH trial sites, despite extension of the drying/heating period.

Conclusions

Thermal stores of 50kWh and 25kWh capacities were designed, manufactured and characterised. Health and safety requirements resulted in operational conditions being modified to lower temperatures and pressures which resulted in slower charging and discharging than planned. Experiments indicate TCS systems have significant potential, with good round trip efficiency possible. The financial case cannot be made unless (i) costs of stores and supporting systems can be manufactured for less than £200/kWh capacity (ii) the number of charge/discharge cycles per annum is high, at least above 100. If grid electricity is used for direct electrical heating (with a COP approaching 1) is used to achieve the high required charging temperatures, competitiveness with stores charged to lower temperatures using heat pumps with seasonal COPs of 2.5 is difficult. Stores charged with onsite generated electricity that would be wasted or sold to the grid at low prices may be more cost competitive. Applications in industry and mobile thermal storage with large numbers of cycles may also be more attractive.

Thermal store controls

The aim of workstream was to leverage Mixergy's existing volume electronics supply chain and software infrastructure to accelerate the deployment of the technology and:

- Bring the controller from prototype design (referred to as Gen 2) to a volume production, market ready version (Gen 3, CE/UKCA compliant).
- Develop a robust software platform to control and monitor devices and facilitate grid support services.
- Successfully demonstrate deployment of the control technologies across trial sites.

Dwelling-level and multi-dwelling controls development

Modular controllers suitable for volume production were developed to facilitate the operation and monitoring of the PCM store. The controller uses the Modbus RTU protocol, a common communication standard used in Building Energy Management Systems (BEMS). It can function as a slave device for a Mixergy home master controller or any third-party BEMS which is compatible with the Modbus protocol.

Modular controllers were developed and built to control and monitor the TCS store adopting a similar Modbus communication approach. The controller manages the TCS charging and discharging cycles and collects measurement data for performance evaluation.

A dwelling-level controller (Home Energy Management Hub) was developed to coordinate the operation of heat pumps, PCM and TCS stores, and hot water cylinders, providing hot water and space heating services within the home.

A multi-dwelling level controller (home-to-cloud infrastructure) was built to enable supervisory control from a cloud or remote server. The cloud platform is interoperable or to be implemented with more advanced control algorithms, such as Model Predictive Control.

PCM modular controller

The PCM and TCS control systems were designed using a Modbus master and slave structure. The Modbus RTU protocol is a widely accepted serial-level protocol within building management systems (BMS) and industrial automation systems due to its ease of use, scalability, and reliability. The Modbus structure for this project is shown in Figure 67.

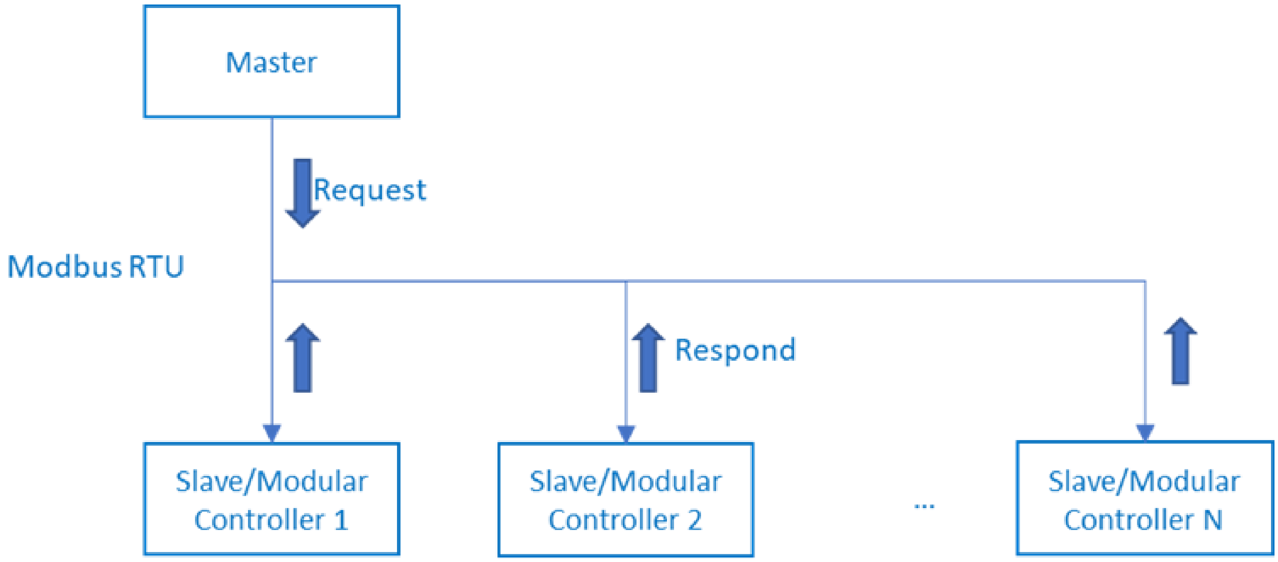

Figure 67: Modbus RTU Master-Slave structure.

The controller carries the basic functionality for each PCM store, such as measuring temperatures at three locations of the store (inlet, outlet, and centre) and flow rate. The modular controller shown in Figure 68 was designed with abundant input and output channels for future functionality expansion.

1. Primary 240V supply
2. Digital pulsed input with 12V DC supply to power and take measurements from the pulsed flow meter.
3. Analogue inputs to measure the resistance of the PT1000 sensors in the PCM store.
4. Two Modbus RTU ports; one goes to another modular device, one goes to the master controller.
5. Redundant voltage-free relay switch in case of using the modular device for heat pump control.
6. Additional analogue inputs for redundancy.
7. 240V switch live port in case of needing to control the motorised valve.
8. Two inline immersion supplies which are designed for TCS application.
9. Onboard single-board computer (to support advanced control algorithm or IoT applications).

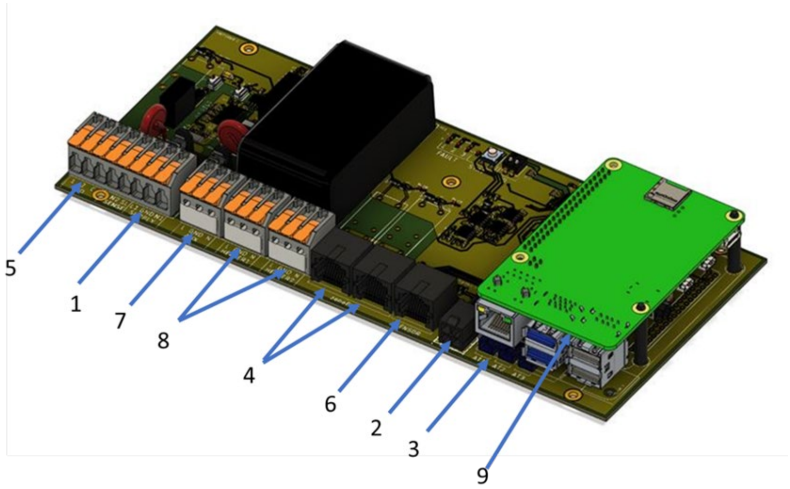

Figure 68: Each PCM controller was tested and calibrated before the installation in-situ. The test set up can be seen in Figure 69

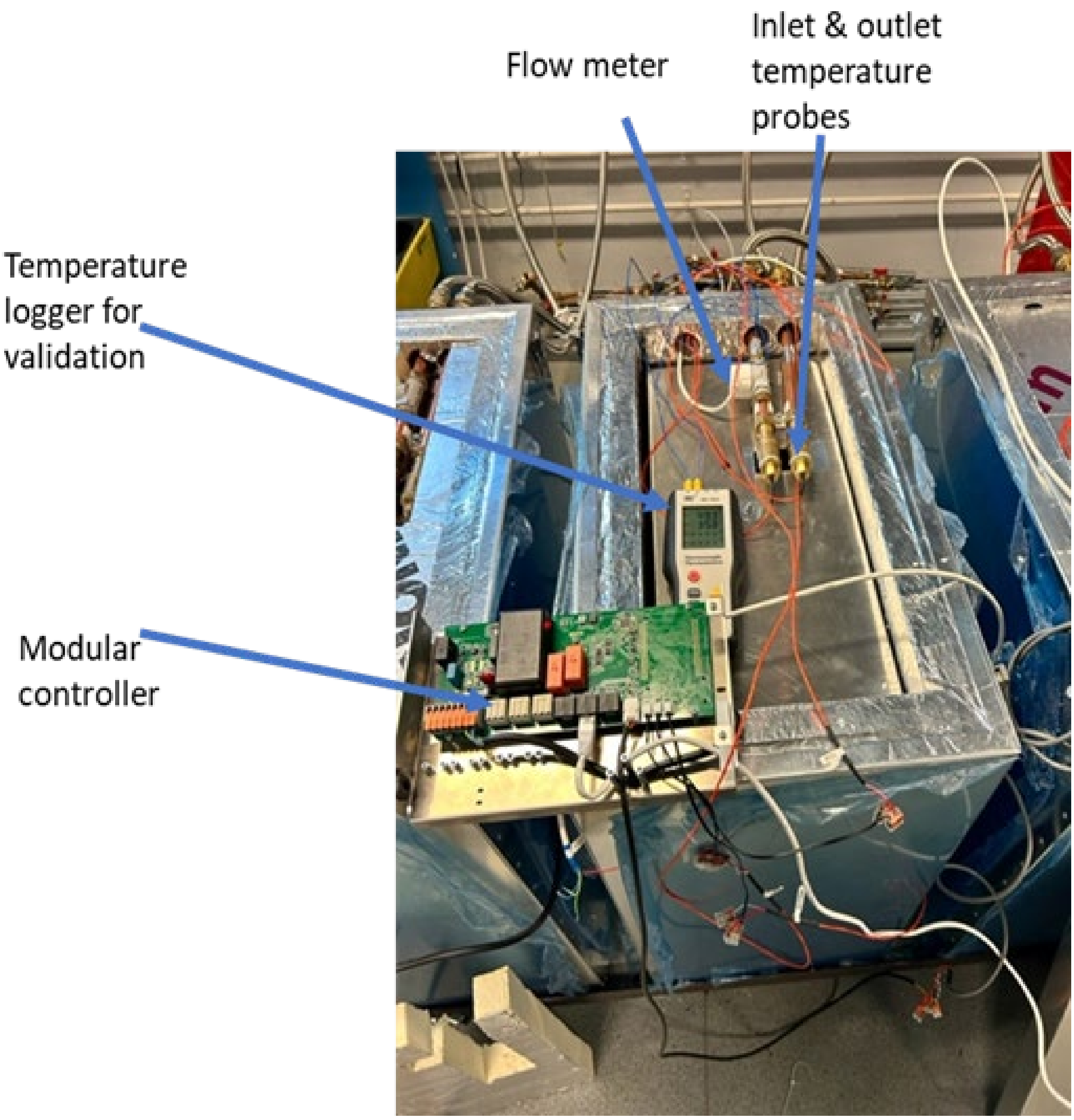

Figure 69: A close up of the PCM controller test set up.

A full UKCA/CE marking compliance process was carried out for this controller to ensure the safety and regulatory compliance of using this controller in the domestic environment.

TCS modular controller

The TCS controller was built as a control due to the instrumentation requirements of the prototype TCS units which will not be necessary in volume production. It was also designed and tested for UKCA/CE marking compliance.

Single dwelling level control

The dwelling-level control was developed and built at two levels. The first level is the single dwelling-level control, where the control takes place within the home and involves a master controller that orchestrates the operations of all heating and hot water service-related devices in the house. The second level is the supervisory (multi-dwelling) control, where a cloud platform (a remote server) and an Internet of Things (IoT) structure are developed and built to control the operation of devices within the home remotely. This enables interactive control between individual households and the electricity grid using online system information (e.g., tariffs, national or distribution-level electricity generation, and demand).

The single dwelling level allows the user to define and control how and when the hot water and heating services are provided. The control system consists of the following key devices:

1. PCM modular controllers which implement basic functionalities for the PCM thermal stores.

2. A TCS modular controller which operates the auxiliary systems and controls the operation of the TCS thermal store on the device level.

3. A zone controller which controls various system zone valves to determine the heat flow within the system (i.e. from the heat pump to the PCM modules, from the heat pump to the hot water cylinder, from the heat pump directly to house space heating circuit, or from the PCM or TCS to the house space heating circuit).

4. A hot water controller which measures the cylinder temperature and controls the heat pump to operate in hot water mode.

5. A third party (smart) room thermostat to allow users to control or schedule space heating on top of Mixergy's master dwelling controller.

6. A Mixergy master controller which runs the control algorithm and determines the system run state. We used a Windows PC with Python scripts to implement the control algorithm. For volume production, this could be implemented through a low-cost single-board computer.

The system can operate the following heating flow scenarios:

- Provide space heating from the heat pump directly.
- Heat the hot water cylinder from the heat pump.
- Heat the PCM stores from the heat pump.
- Heat the TCS store from the inline electric immersion.
- Heat the hot water cylinder from the PCM store (when the store is fully charged).
- Heat the hot water cylinder from the TCS store (when the store is fully charged).
- Provide space heating from the PCM store (when the store is fully charged).
- Provide space heating from the TCS store (when the store is fully charged).

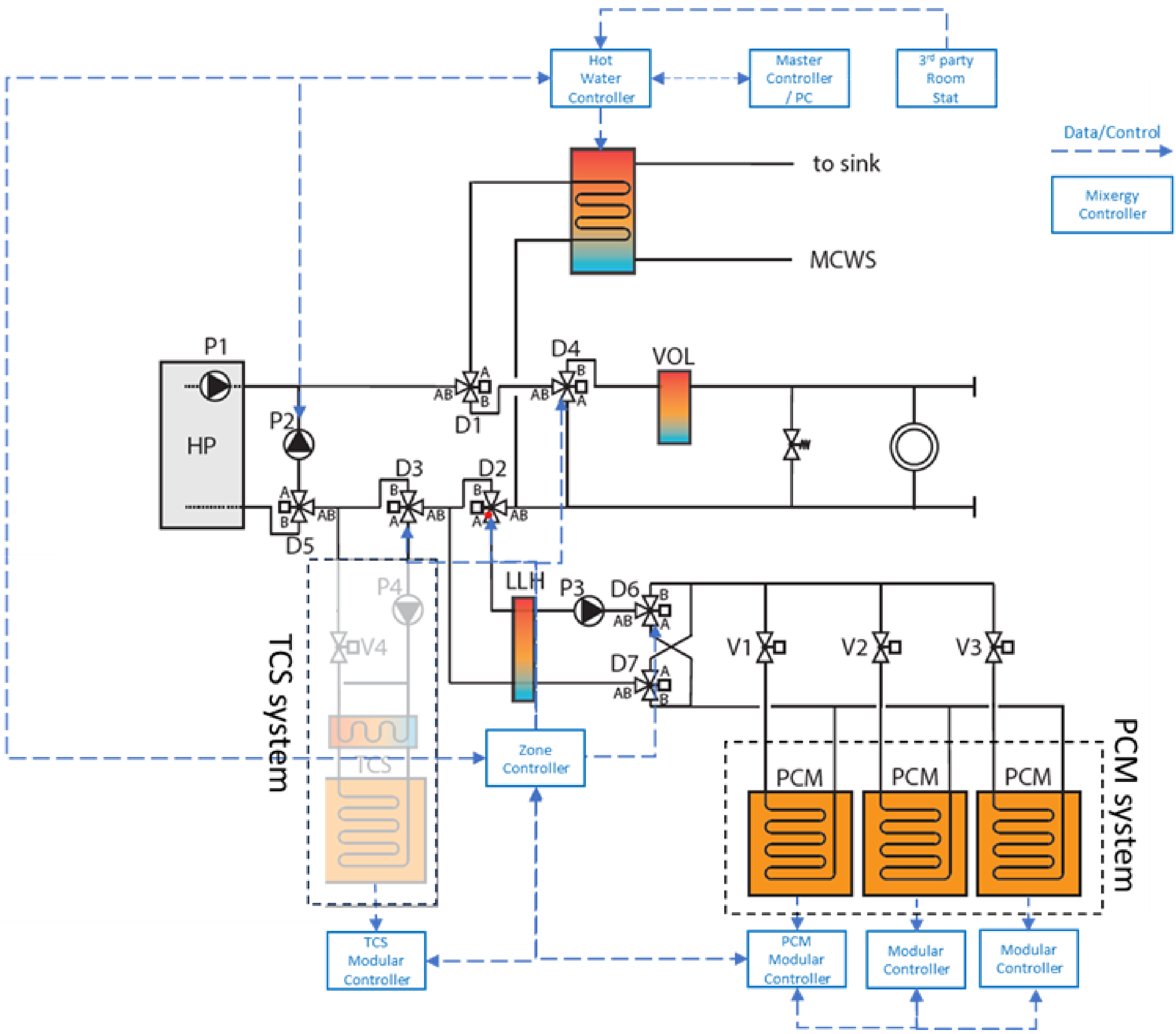

Figure 70: The system diagram of the connection and data flow along with the physical master and slave devices.

The dwelling system control schedule runs in real-time (loops every 5 seconds), and follows the principles below:

- ASHP will heat up both the hot water cylinder and PCM stores when the tariff is cheap.
- During daytime peak tariff periods, the PCM stores will be used first to satisfy the space heating and hot water demand (when the hot water cylinder is cold). The ASHP will only be activated when the thermal energy inside PCM stores is depleted.
- User can schedule or boost space heating using a third-party room thermostat. This will overwrite the existing control, prioritising customer comfort.

Supervisory multi-dwelling level control

The supervisory multi-dwelling control involves a cloud platform (a remote server) and the corresponding IoT infrastructure to control and monitor the operation of multiple dwellings simultaneously. This enables each home to actively respond to the real-time electricity network (i.e. provide demand side response service) conditions and allows users to capture value from the electricity market such as time-of-use tariffs.

The multi-dwelling control infrastructure illustrated in Figure **71** consists of:

1. Server (or central controller) - developed by Mixergy to operate the multi-dwelling control algorithm and communicate with all connected dwellings. It sends control commands in the form of two control byte packets to the dwelling's master controller and receives system data in JSON format using TCP/IP to ensure reliable and secure data transmission.

2. Dwelling master controller - collects data from devices and sends to server for monitoring and control purposes; takes commands from the server and passes them on to the relevant slave controller in the dwelling.

3. Dwelling slave controllers (PCM store, TCS store, hot water, and zone controller) - manage specific energy systems and execute commands from the dwelling master controller.

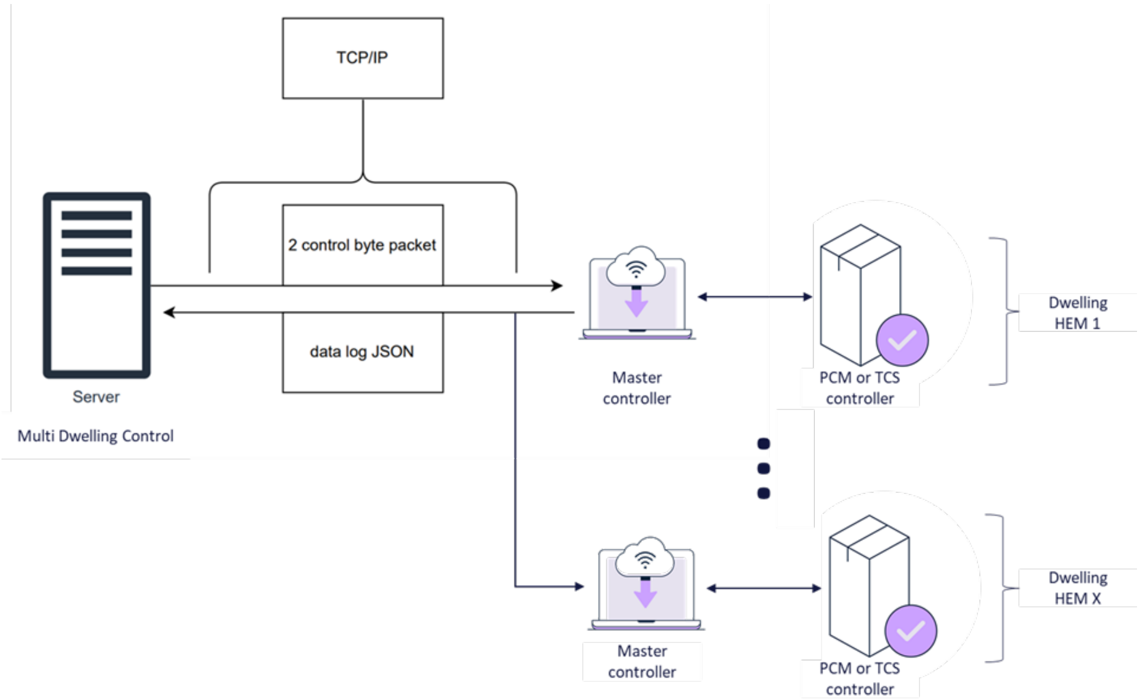

Figure 71**: The infrastructure of the multi-dwelling control system.**

The infrastructure can be integrated into Mixergy's current Home Energy Management System – HEMS – (in Figure 72) alongside control for smart hot water cylinders, heat pumps, PV inverters, and EV chargers, offering grid flexibility services without adding significant costs or changes to its existing infrastructure.

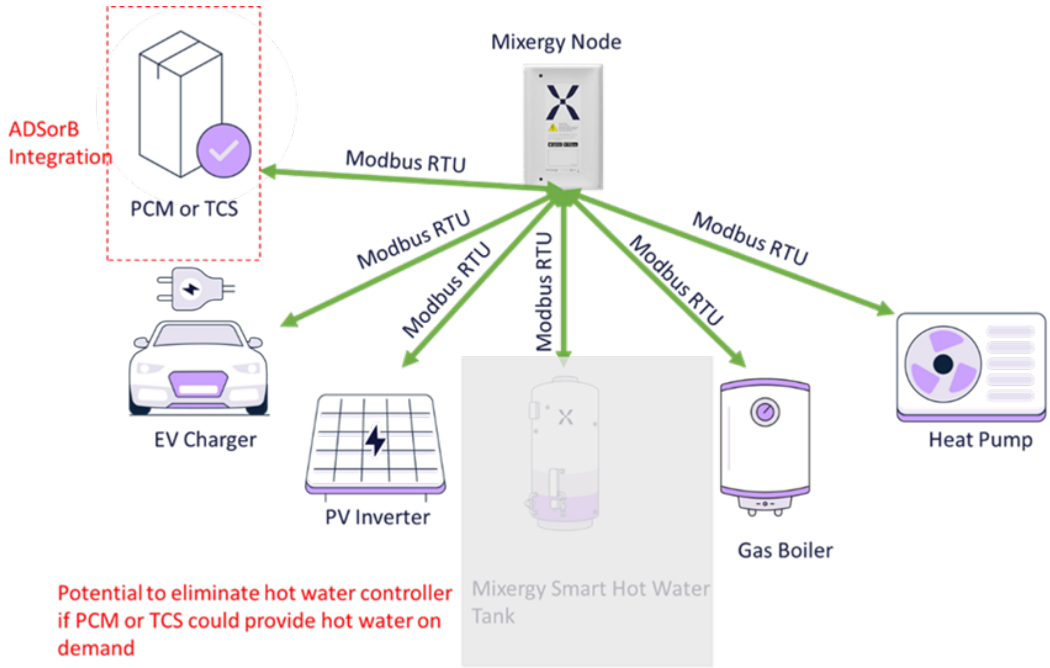

Figure 72: **Integration of the ADSorB controller into Mixergy's existing ecosystem.**

Production-ready controller design and supply chain development

The final controller design advanced the project prototype to a stage where it is regulatory-compliant, commercially viable, and ready for volume production. This process involved optimising the design for volume manufacturing, ensuring compliance with relevant standards and identifying a reliable and cost-effective supply chain.

To achieve regulatory compliance and confirm that the controllers are safe and reliable to operate within the EU and UK market, Mixergy completed the UKCA and CE marking processes for both the PCM and TCS controllers. The production-ready design would allow the controller to be manufactured in volume at a lower cost at around £240, down from the £940 cost of prototypes.

Lessons learned

- **More comprehensive state of charge estimation for the TCS store.** The current system uses a limited number of temperature probes and flow meters for estimation, limiting measurement accuracy and increasing control complexity. Work conducted on the PCM stores has shown the value of a physics-informed parameter estimation approach, and this should be extended to the TCS system as data becomes available.
- **The hydraulic system could be redesigned with relocation of the thermal buffer vessel.** This would significantly simplify the control approach.
- **Better integration with heat pump controls.** The current system uses a "switch live" signal to request demand “on” or “off” from the heat pump. While this method works, system efficiency could be further improved by implementing more refined control through Modbus integration.

State of Charge (SoC) estimation

The ability to accurately estimate the state of charge (SoC) of a storage device is key to maximising its operational efficiency, and particularly so for the case of thermal stores deployed alongside highly optimised heat pump systems. Traditional methods for estimating SoC for PCM-based storage systems face significant limitations. Temperature-based methods only provide localised measurements and thus require multiple sensors to achieve global estimates. More critically, they are insensitive to the state of charge within the latent phase. This section briefly describes two approaches that have been investigated for overcoming these challenges within the ADSorB project. The first is an online estimation technique that enables continuous prediction of the expected energy recoverable from the system, even during idle states. The second is exploration of an alternative vibration-based sensing technique that offers an alternative mode of detecting phase changes within the storage system.

Technical outputs

Online estimation methodology

The analysis of predicted recovered energy is crucial for understanding the efficiency and capacity of an energy storage system. Predicting the amount of energy that can be recovered after charging provides insights into the system's operational effectiveness, particularly in optimising charging and discharging processes. This analysis helps to evaluate how much energy the system can store and subsequently utilise during the discharge phase. By comparing predicted recovered energy with actual power data, we can assess model accuracy, identify potential inefficiencies, and refine strategies for SoC estimation.

To achieve accurate results, in this analysis, the predicted recovered energy is obtained by combining a physical model with experimental data. The inputs to the model are the thermal powers transferred into and out of the store during, respectively, charging and discharging phases. The model parameters are charging and discharging efficiency, and a standing loss factor. These parameters may be estimated from training data; in this study, least squares estimation is applied. The discrete-time physical model used to predict the energy recoverable is described by,

$$E_{pred}^{t} = k_{loss}E_{pred}^{t-1} + (\eta_{ch}P_{in}^{t-1} + \eta_{dch}P_{out}^{t-1})\Delta t$$

where E_{pred}^{t} is predicted recoverable energy at time t; Δt is the time step between current and previous time points; P_{in} and P_{out} are respectively the thermal powers into and out of the store; $\eta_{ch}$and $\eta_{dch}$are the charge and discharge efficiencies; and k_{loss} is the standing loss factor. With the model form set, attention turns to finding appropriate values for the unknown parameters on the model (k_{loss}, $\eta_{ch}$and η_{dch}). For this initial study, the parameter estimation task is simplified by assuming $\eta_{ch} = \eta_{dch}$. Parameters are estimated using the least squares method, which seeks to minimise the sum of squared errors between the predicted energy (E_{pred}) and actual recovered energy (E_{actual}) at those points that may be observed, given by,

$\frac{1}{n}\sum_{i=1}^{n}(E_{actual,i} - E_{pred,i})^2$

where n is the number of observations used for fitting the parameters. It is assumed that each full charge-discharge cycle generates three such observations: $E_{actual} = 0$ at the start of charging and end of discharging, with the value of E_{actual} at the start of discharging being of greatest value. This value is calculated by numerically integrating the discharge powers observed during the discharge period.

Experimental implementation

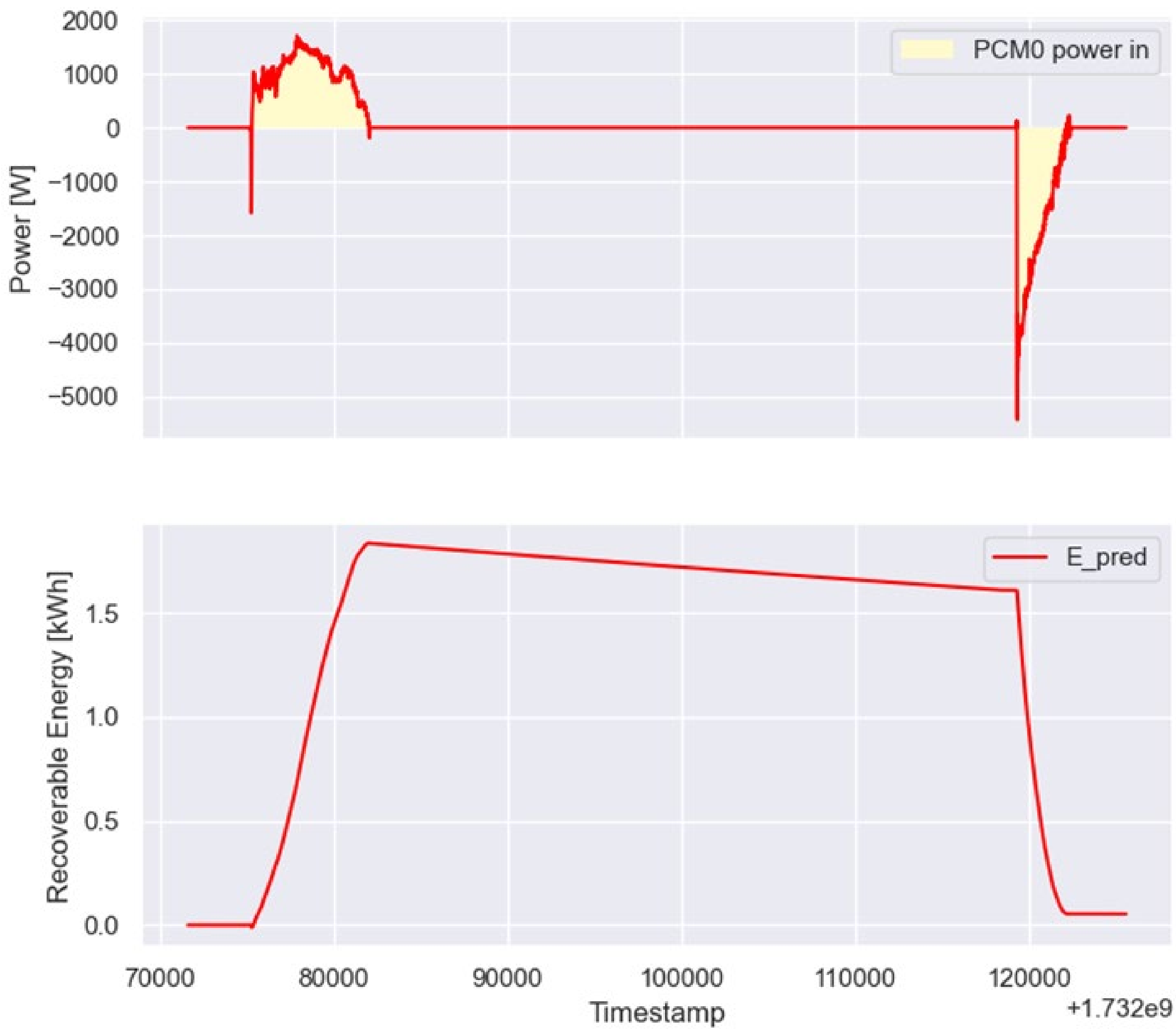

Figure 73: Example of SoC fitting using the online estimator. The upper plot shows the charge and discharge powers used for fitting. The lower plot shows the predicted recoverable energy returned by the estimator.

Figure 73 illustrates the approach developed. The top plot shows the observed charging and discharging power, while the bottom plot represents the predicted recoverable energy following the fitting of k_{loss}, η_{ch} and η_{dch}.

Fitting occurs based on E_{actual} actual values at the three time points identified above: start of charging, start of discharging and end of discharging. In this example, numerical integration over the discharge period indicated a total recovered energy of 1.61 kWh. The predicted SoC curve is consistent with physical expectations, and there is scope for extending the adopted model form to further account for expected physics (for example where the store operates in varying ambient conditions). Operational deployment of the online SoC estimator based on the fitted model has been demonstrated on the main controller within the LCL, with estimates returned alongside other controller logging outputs from the Mixergy system.

Outcomes

This section highlights the transition to online methodologies for tracking the SoC in energy storage systems. The approach sets up real-time SoC tracking by integrating physical models with experimental data, allowing continuous learning with each cycle. This enables iterative improvement, as every charging and discharging cycle adds data to refine model fitting, ensuring dynamic adaptation to system behaviour. By embedding these online estimation methods into the LCL code, the system gains the capability to support more advanced modes and higher-priority tasks, enhancing overall operational efficiency and enabling deployment in diverse scenarios. The next step for the work is to validate the model and ensure its robustness by conducting a leave-one-out cross-validation (LOOCV). This approach will evaluate the model's predictive accuracy by iteratively using all but one dataset for training and using this excluded dataset for testing. By employing this approach, we can better understand the energy accumulation dynamics, improve the accuracy of SoC estimation, and ultimately enhance the performance of the energy storage system.

It is noted that whilst the methods have been developed in the context of the PCM stores, they may be generalised to other thermal storage systems. In all cases, the quality of the predictions made may be increased through either (i) incorporating further physics-based insight into the underlying model or (ii) increasing the information content of the data used for training.

Alternative sensing

The challenges associated with SoC estimation for PCM stores using temperature sensors alone has been noted previously. One method for estimating the SoC of general thermal energy storage (TES) units is to utilise temperature sensors positioned at the inlet and outlet flows, allowing charge and discharge powers to be calculated when combined with a flow meter. However, this approach cannot provide SoC estimates when the PCM units are idle. Alternatively, internal temperature sensors embedded within the active materials may be employed to monitor SoC in both when in operation and idle. However, these sensors are inherently limited to localised measurements, requiring multiple sensors to obtain a global SoC estimation, and are insensitive to the SoC of the store when the PCM is in its latent phase. To overcome these challenges, a vibration-based sensing approach for SoC estimation was developed.

Technical outputs

Methodology

As illustrated in Figure 74, a beam is attached to the base of a PCM unit, and its vibrational response is used as an indirect measure of SoC. The method is benefited from the changes in boundary conditions caused by the state transitions of PCM materials. When the state of a PCM material changes from solid to liquid, the effective stiffness of the beam attached significantly increases. By considering the fundamental vibration mode of the beam as a single-degree-of-freedom (SDOF) system, this stiffness change can be observed as a shift in the frequency response of the beam. This approach could offer a practical and cost-effective alternative for SoC estimation, eliminating the need for many internal temperature sensors while providing continuous tracking regardless of the operational state of the PCM unit.

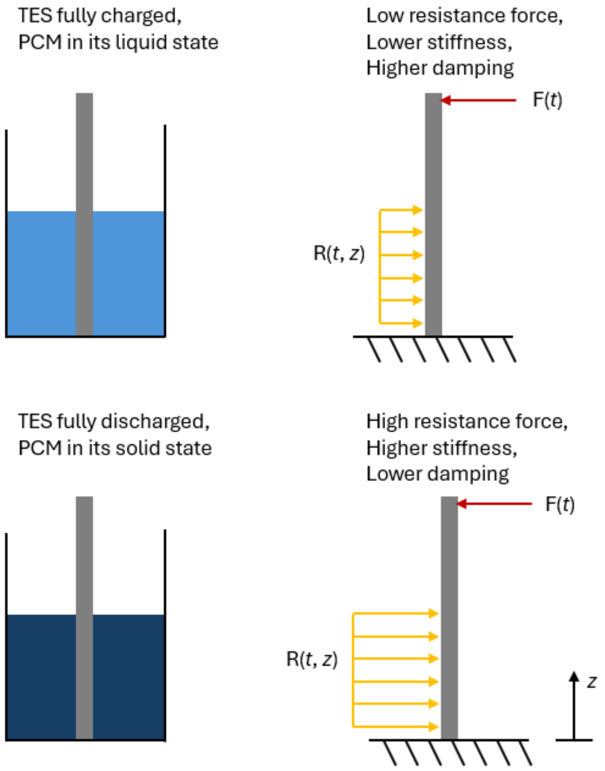

Figure 74: Illustrative overview of the vibration-based SoC estimation approach. Excitation forces are shown in red, with reaction forces from the PCM in yellow.

Experimental application

To demonstrate the practical applicability of this approach, a simple experimental setup was constructed to simulate the operation of a PCM unit in a controlled laboratory environment, using CrodaTherm 53 to mirror the full-size stores. This was poured into a transparent, plastic-based enclosure for visual observation of material state transitions. The enclosure was mounted in an environmental chamber using rubber-pads to reduce vibrations from other sources.

A steel beam (3mm diameter, 100mm length) was sealed at the enclosure base with an elastic connection component to prevent any leakage issue in liquid state. An accelerometer was fixed to the free tip of the beam to record vibrational responses. To determine a suitable excitation frequency, impact tests were performed in both liquid and solid states of the material, with the results shown in Figure 75. It was determined that an excitation frequency smaller than 100Hz would be effective in distinguishing solid and liquid states.

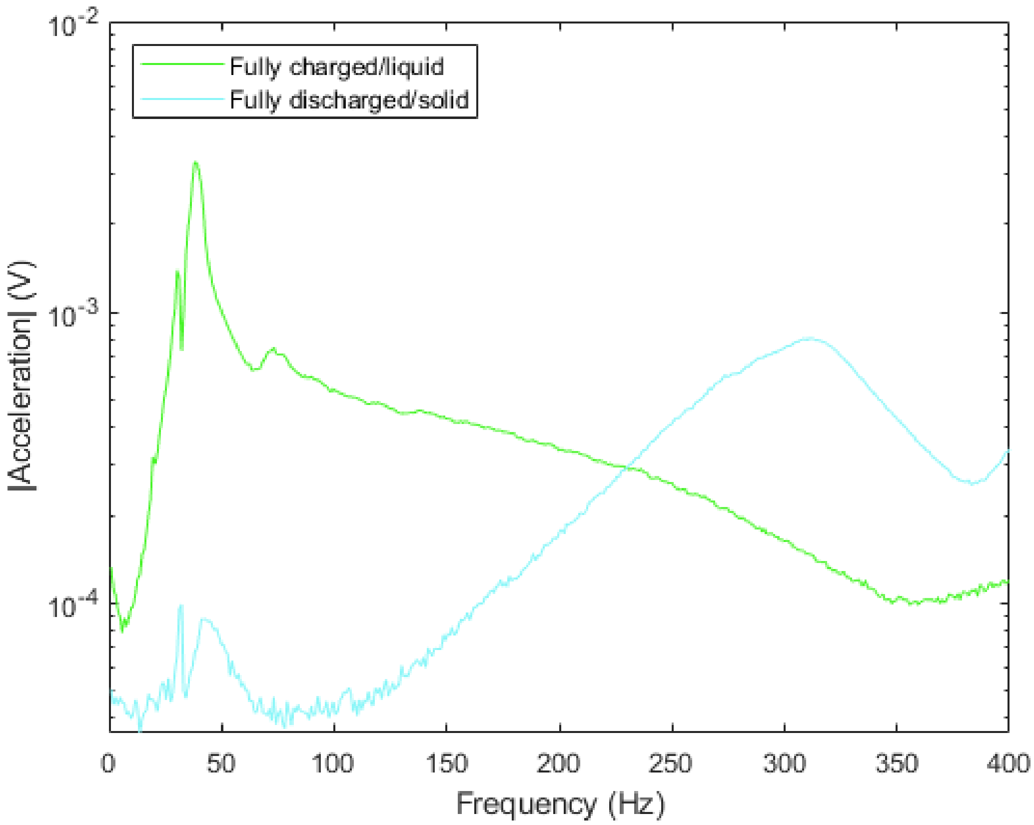

Figure 75: Frequency-domain impact responses of the beam.

Vibrational excitation was achieved by using a rotating unbalanced mass mounted near the free tip of the beam. The rotating unbalanced mass was powered from a power amplifier and the excitation voltage was set to 1.8V which was equivalent to an excitation frequency of ~95Hz. To observe a large number of vibrational cycles, accelerometer data was recorded for 10 seconds at a 1kHz sampling rate in the measurements. Tests were initiated at room temperature when the PCM was in a solid state (discharged). The temperature was gradually increased to achieve a fully liquid (charged) state and then reduced to return back to a fully solid state.

Results and discussion

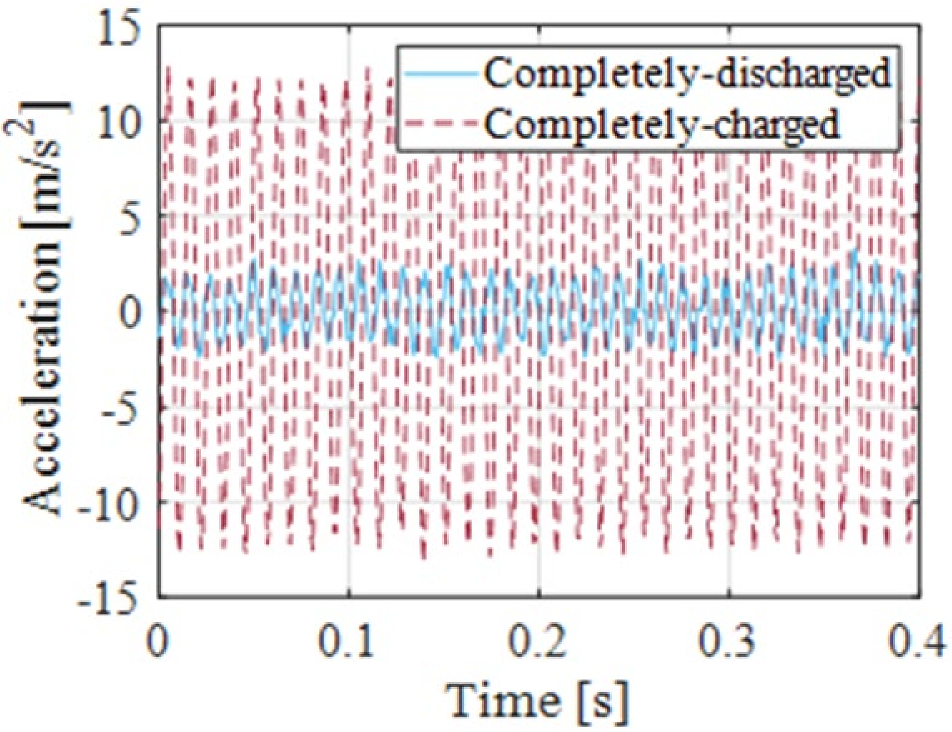

Figure 76: A segment of the recorded acceleration signals in both discharged and charged states.

Figure 76 shows the measured acceleration signals for completely discharged and charged material for the first 0.4 seconds. It is apparent from this graph that the completely discharged material (solid state) produces larger acceleration responses than the completely charged material (liquid state). This indicates that the pre-assumption of the effective beam stiffness reduction shown in the methodology is valid.

The measurement results of temperature ramping-up and ramping-down are set out in Figure 77 and Figure 78, respectively. In these plots, three different methods are used for presenting the resulting acceleration amplitude to both provide flexibility in the SoC estimation method and observe any deviations. The vibration-based approach results of Figure 77 demonstrate that the material state changed from solid to liquid between 12.30 and 13.30. Figure 78 shows that the material state changed from liquid to solid between 15.30 and 16.00. Phase changes were verified by visual inspection, with examples of the test sample in both charged and discharged stated presented in Figure 79.

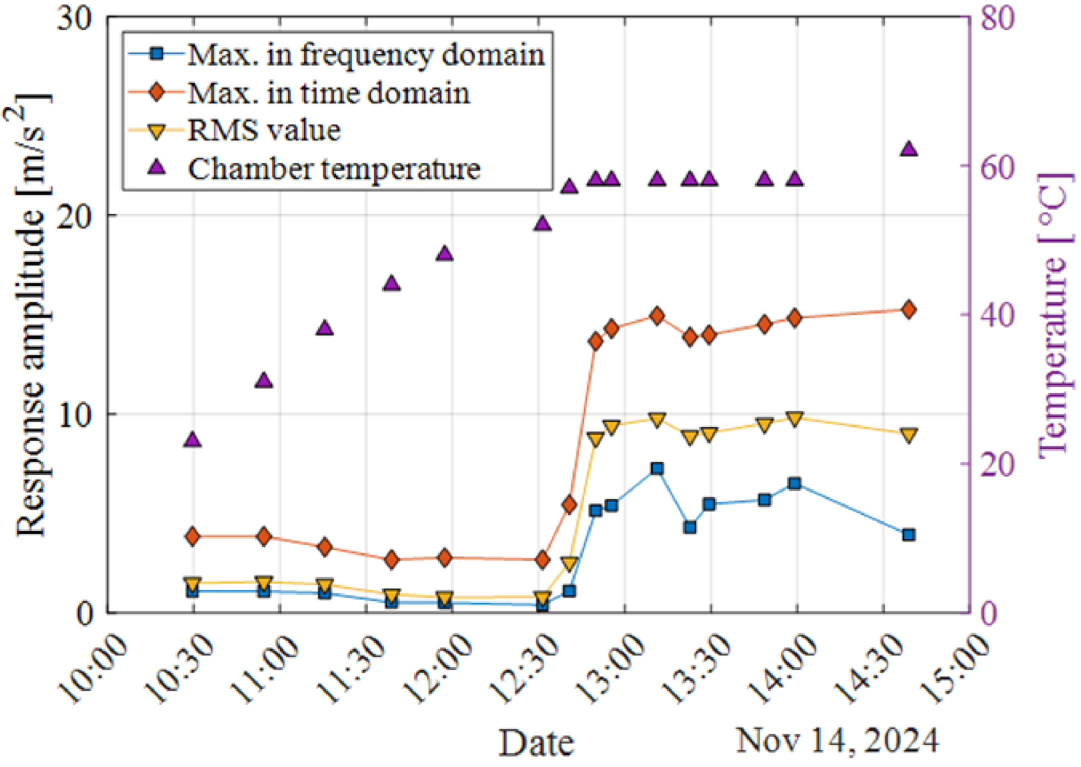

Figure 77: Measurement results while temperature ramping-up.

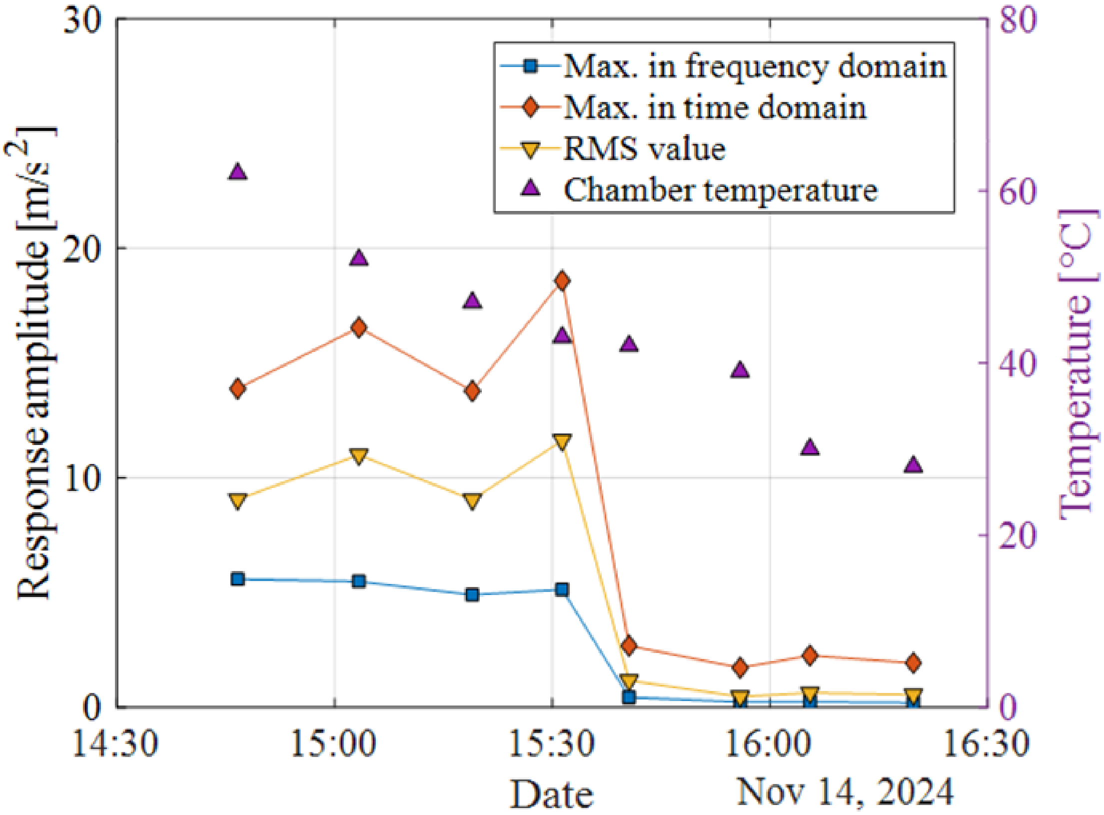

Figure 78: Measurement results while temperature ramping-down.

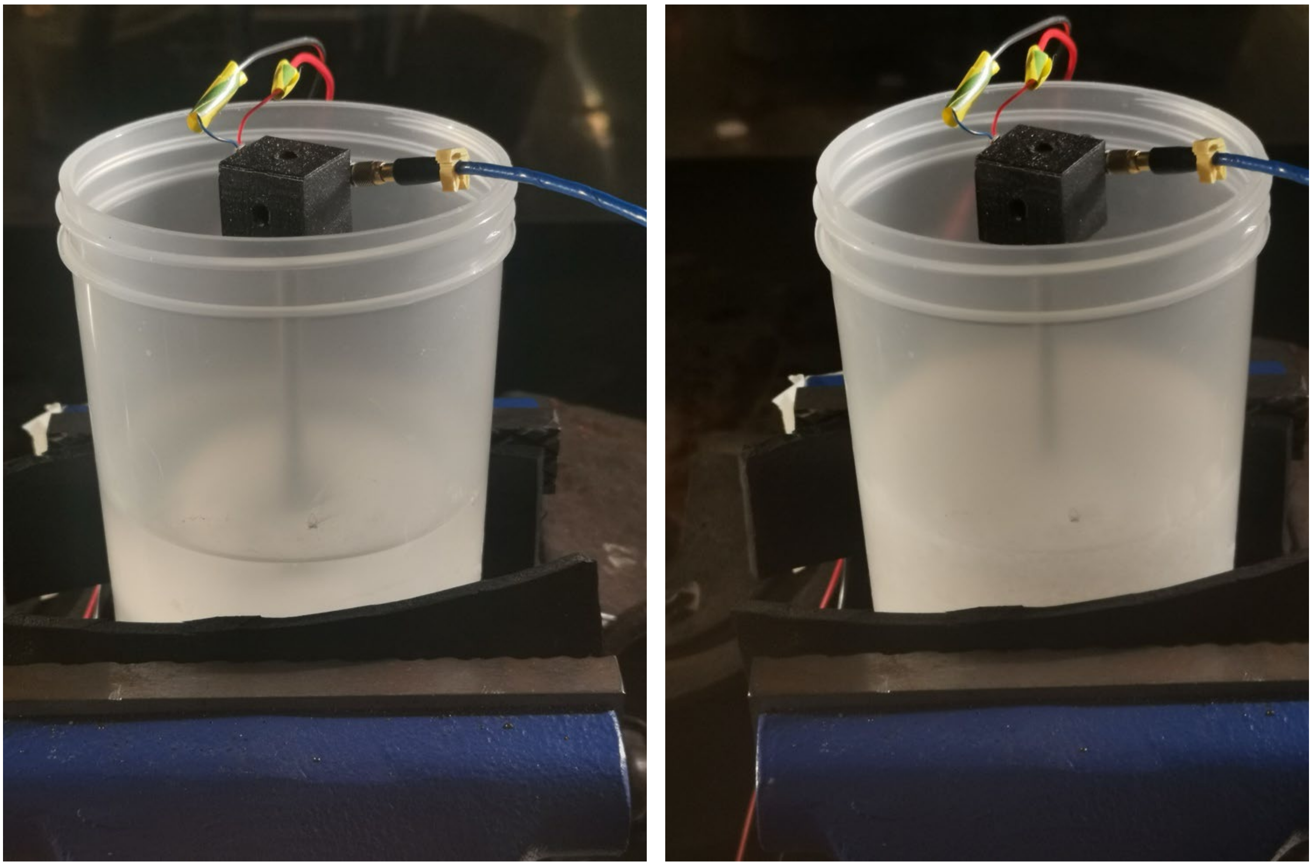

Figure 79: Images of test sample taken whilst in a charged/liquid state (left) and a discharged/solid state (right).

Outcomes

It has been demonstrated that a novel vibration-based sensing methodology is capable of identifying the onset of phase transitions, and also demonstrates sensitivity to changes within the latent phase. Valuable steps forward have been made in both the physical system setup (principally the adoption of a rotating mass excitation device) and the associated signal processing methodologies. Time domain amplitude responses have been identified as thanks to their sensitivity and simplicity; they would be straightforward to implement in a commercial solution as they have very low computational requirements, with no signal processing/spectral estimation required. The approach is still at a comparatively early stage of development but, if successful, would represent a valuable addition to the set of sensing modalities available for online estimation of PCM SoC. The next step for this work is to build a more comprehensive set of test data with a focus on data gathering during the latent phase. If successful, this would be followed by a test programme on a more representative PCM system, ideally through retrofit to one of the manufactured Gen 1 or Gen 2 PCM stores.

Conclusions

This section has briefly described the development of SoC approaches applicable to PCM storage. Both approaches show distinct promise, with the online estimation technique having been demonstrated to be effective using data from the laboratory-based systems. It is noted that whilst this approach has been developed in the context of the PCM stores, it may be generalised to other thermal storage systems. There remains scope for additional work to more thoroughly evaluate the performance of the approach and to develop it further, with an expectation that the quality of the predictions made using the technique may be increased through either (i) incorporating further physics-based insight into the underlying model or (ii) increasing the information content of the data used for training. The alternative sensing work has successfully demonstrated a novel approach to detecting phase changes within a PCM sample, with minimal requirement for advanced signal processing. Further work is required to progress this beyond proof-of-concept stage, and to more thoroughly evaluate the commercial case for this technology.

Embodied carbon analysis

In order to support the commercialisation case and to build an understanding of the sustainability of the developed technologies, an embodied carbon (EC) analysis was conducted by researchers with expertise in life cycle assessment (LCA) at The University of Sheffield. This enables a preliminary comparison to be made between the carbon expended in manufacture of the developed PCM and TCS stores versus competing domestic energy storage technologies, both electrical and thermal. The brief conclusion drawn was that the newly developed PCM stores were comparable to existing hot water tank stores on an emissions per kWh of storage (kgCO2e/kWh) basis, with TCS having the potential to offer substantially reduced emissions per unit of stored energy if target storage capacities can be achieved. All of the thermal storage technologies considered greatly outperformed EC values for the principal electrical alternative (a Li-ion battery) drawn from the adopted product database, although it was noted that lower Li-ion EC values are stated in some academic literature.

Technical Outputs

Total embodied carbon for PCM and TCS stores

To calculate the embodied carbon of the stores, each material must be assessed. The masses of the principal store components were calculated using information from Loughborough University supported by physical measurements where required. The embodied carbon of the steel, copper, aluminium and insulation were calculated using the Inventory of Carbon and Energy (ICE) database V4.0, which is based predominantly on data contained within Environmental Product Declarations.

The embodied carbon values for copper and aluminium were taken from the ICE database as being 2.71kgCO2e/kg and 6.58kgCO2e/kg respectively. The embodied carbon of the PIR insulation used in the PCM store was taken as 3.09kgCO2e/, and the value for mineral wool insulation used in the TCS store was taken as 1.25kgCO2e/kg. The value for the electrogalvanised steel used in the PCM stores was taken to be 2.71kgCO2e/kg, with a value of 1.64kgCO2e/kg for the engineering steel used in the TCS pressure vessels.

To calculate the embodied carbon associated with the phase change material and thermochemical material used within the stores, the LCA software SimaPro was used which contains a more extensive database of materials. The exact physical and chemical compositions of these materials was not openly provided by manufacturers, and therefore the closest comparable materials were chosen based on the known characteristics. For the PCM material, a mean was taken of two comparable materials and the embodied carbon estimated to be around 5kgCO2e/kg. For the TCS material, a mean was taken from six materials, resulting in an embodied carbon estimation of 2.7kgCO2e/kg. These figures are early approximations, hopefully indicating the expected range that the embodied carbon of these materials would fall into. The total embodied carbon, embodied carbon per kWh, and the embodied carbon per component material are shown in Table 5.

Table 5: Embodied carbon of the PCM and TCS stores (all values kgCO2e)

Store	Steel case	Alu case	Cu HX	Alu HX	Steel HX	Insulation	PCM/ TCS	Total
Gen 1 PCM	137.3	N/A	23.1	17.3	1.6	3.9	199	382
Gen 2 PCM	143.2	N/A	23.1	17.3	1.6	6.6	224	415
Gen 1 TCS	377.2	N/A	44.5	114.0	N/A	10.6	507	1053
Gen 2 TCS	203.4	N/A	19.5	61.6	N/A	5.2	243	533
Gen 2.1 TCS	N/A	430.8	19.5	61.6	N/A	5.2	246	763

The results show that out of the two PCM stores, Gen 2 has the higher embodied carbon due to the larger volume of the vessel and higher mass of materials used. Similarly, the Gen 1 TCS store returned the highest embodied carbon out of the three TCS stores due to its significantly larger size. When looking at the store components individually, the largest contribution to total embodied carbon was the active material, whether PCM or TCS. There may be scope for reducing this value through consideration of other alternative materials or lower carbon production methods for these elements; this must be weighed against the performance of the material. The second largest contribution for all stores was the material used for the casing; with scope for substantial optimisation of casing design for both the PCM and TCS. The results in Table 5 focus on embodied carbon per whole store; embodied carbon per kWh of functional capacity will be considered in the following section.

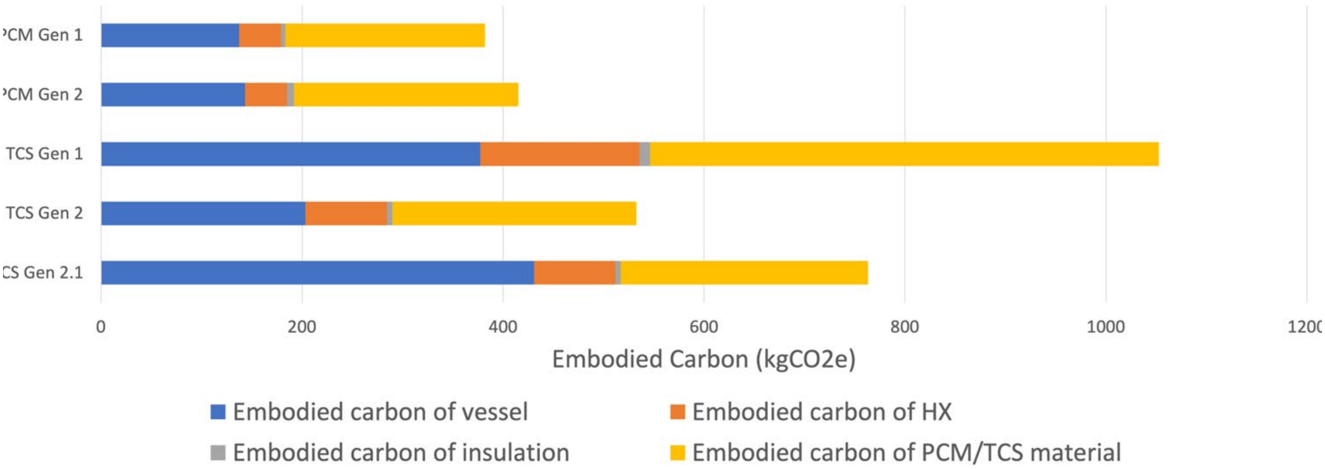

Figure 80: Distribution of embodied carbon contribution by material group

Figure 80 shows the distribution of embodied carbon across the stores for the main components, including the vessel, heat exchanger, insulation, and PCM/TCS material. By building the TCS Gen 2.1 vessel in aluminium rather than steel, the mass of the store decreased by 25% from the TCS Gen 2 store, however the embodied carbon increased by 43%.

Comparison to existing technologies

An initial comparison between the new PCM and TCS stores and existing energy storage technologies such as lithium-ion battery stores and hot water storage tanks is presented in Table 6

Table 6: Comparison of PCM and TCS stores with a Li-ion batteries and water storage tanks

Store	Dimension mm	Mass kg	Capacity kWh	Total kgCO2	Total kgCO2e/ kWh
Gen 1 PCM	785 x 310 x 610	109	4.2	382	91.1
Gen 2 PCM	750 x 365 x 660	117	4.5	415	91.3
Gen 1 TCS	2000 x 600 x 600	455	50.0	1053	21.1
Gen 2 TCS	990 x 600 x 600	232	25.0	533	21.3
Gen 2.1 TCS	990 x 600 x 600	173	25.0	763	30.5
Lithium-Ion battery	1970 x 650 x 587	536	37.4	10900	291.4
Water Tank (ACV Smart E plus, 300l)	2050 x 565 x 565	87 (empty)	10.3	388	37.9
Water Tank (ACV HRi600, 600l)	2095 x 703 x 703	220 (empty)	20.5	937	45.7
Water Tank (Mileo, 300l)	1800 x 610 x 610	113 (empty)	10.3	516	50.3

Environmental performance declarations sourced from PEP Ecopassport of one lithium-ion store (Galaxy Lithium-ion Battery Cabinet, Schneider Electric) and three water tanks (Smart E Plus and Hri 600, ACV and Mileo + 300, Atlantic) were chosen for comparisons. The product stage embodied carbon for each product can be seen in Table 6. Energy capacities for the hot water tank stores were based on raising the stated water volume of store by 30°C (e.g. from a source temperature of 20°C to a stored temperature of 50°C), with charging, discharging and standing losses neglected. It should be noted that there is significant variability in the reported values of embodied carbon associated with Li-ion batteries. Literature on the global warming potential of lithium-ion batteries presents the embodied carbon at a range between 54kgCO2e/kWh and 115kgCO2e/kWh This is noticeably lower than the value for the Li-ion battery store sourced from the PEP Ecopassport data (291kgCO2e/kWh) and highlights the challenges in conducting EC analysis on emerging technologies.

Outcomes

The lithium-ion battery has the highest embodied carbon of the compared stores, returning a value over three times greater than any other store when considered per kWh. It is worth noting, however, that this is the only store providing electrical (i.e. kWh_{el}) rather than thermal (i.e. kWh_{th}) storage. A unit of electrical storage may be thought of as being of higher value than a unit of thermal storage as it is of greater utility; for example, it may subsequently be converted to heat using a heat pump, with an associated COP advantage.

As whole stores the PCM and TCS stores perform similarly to the water tanks. However, when calculated considering the stores functional capacity (kWh), the TCS stores returned a much lower embodied carbon per kWh than the PCM stores. Out of all the proposed stores, the TCS store featuring steel cases were found the most carbon efficient per kWh stored, with both Gen 2 and Gen 2.1 returning values of around 21kgCO2e/kWh. The key caveat here is that these values are dependent on the stated target capacities being achieved in practice; as highlighted in the Thermochemical store (TCS) section, further development is required in order to do so. Nonetheless, it is worth noting that the TCS would remain competitive with hot water storage on an embodied carbon basis even if achievable capacities were reduced by a factor of 2-3.

The returned EC values for the PCM stores were around twice those of the hot water tank baseline, with this being broadly attributable to the active material used (an organic PCM versus water, which was assumed to be “zero carbon”). The PCM EC values were around 3 times lower than the value returned for the considered Li-ion battery.

A key recommendation is that comparisons with more examples of existing storage systems should be carried out to better understand how the performance of the novel stores stand up against already available options. Secondly, a full LCA would enable the significance of the EC contribution to be weighed against those of other product life stages, and the carbon benefit provided through storage.

Conclusions

The analysis conducted in this section provides a useful initial indication of the comparative levels of embodied carbon within domestic energy storage technologies. A preliminary conclusion that can be drawn is that the developed PCM stores may be considered broadly competitive with equivalent hot water storage systems in this regard. TCS has the potential to offer very low levels of embodied carbon if target storage capacities can be realised. All thermal storage technologies were found to offer substantially lower embodied carbon values than the Li-ion battery used for comparison, with the caveat that there is significant variability in reported EC values for such devices.

The embodied carbon value that has been calculated for the PCM and TCS stores and competing technologies only considers the product life cycle stages A1 (extraction of raw materials), A2 (transport to manufacturer), and A3 (manufacture); sometimes referred to as the “cradle-to-gate” stage. It omits the remainder of stage A (onward transport and installation), and the totality of stage B (use stage, including energy use, maintenance, refurbishment and replacement) and stage C (end of life, including recycling and final disposal). To better understand the environmental impacts of the stores, a full life cycle assessment would need to be undertaken, considering every stage of the products lifecycle, from raw material extraction to end of life.

Commercialisation and route to market

The broad aim of the commercialisation workstream was to test and validate the DSR and price arbitrage value proposition presented by the storage devices, and to establish routes to commercial exploitation with different stakeholders. The objectives were:

- Establish supply chain readiness for the controller unit and thermal stores.
- Commence route to BRE endorsement on SAP for the price arbitrage or inter-seasonal benefits for cuboidal thermal storage unit.
- Establish the value propositions of the cuboidal thermal storage with the installers and customers.

It was found that the TCS proposition is particularly challenging in its current form, although there may be route to viability in non-domestic applications once the technology matures. The case for the PCM proposition is more promising, although the cost and relative complexity of the current implementation may place it at a disadvantage versus other technologies in SAP. However, the simplified active buffering implementation proposed in this section has the potential to aid commercial viability through improving system performance and minimising capital and operational costs.

It has been shown that successfully implementing such an approach could enable the cost of heat from an ASHP coupled to a PCM system to be brought appreciably below that for a gas boiler using currently available tariffs; and that such an implementation could be competitive with alternatives storage technologies.

Commercial development: current proposition

Mixergy engaged with installers, customers, regulatory authorities, and other key stakeholders to explore the value proposition of the PCM and TCS stores, particularly associated with the smart control of the thermal stores. The work included:

- CPD training to Mixergy-approved installers and evaluate the value proposition of thermal stores, focusing on tariff arbitrage and cost-reduction measures.
- Engage with BRE to explore the feasibility of SAP endorsement for the thermal stores. The initial discussion led to a focus on Mixergy’s smart thermal storage control.
- Further identify the supply chain for the PCM and TCS thermal store systems, particularly the controller components.
- Assess the commercial viability of TCS and PCM thermal store systems, recommend a route to market, and outline future actions.

Commercial outputs

CPD training outcomes

Mixergy engaged with installers and their customers through a series of webinar-based CPD training. The key findings from the webinars were:

- The installer used to be the gatekeeper of the hot water and space heating appliances purchase, however, we are seeing a rising trend of end customers who are doing their own research and deciding what appliances to install. It is therefore important to engage both installers and customers.
- More than half of the audiences (or their clients) were aware of smart tariffs. However, the majority of them could not quantify the savings on energy consumption and costs.
- Knowing the potential operating cost saving of the smart thermal stores utilising price arbitrage could significantly improve the chance of customers' adoption. Before the CPD training, there were only 40% of installers/customers who would go with the smart thermal store against the cheap, unintelligent thermal store. This number increased to 70% after the CPD training.
- It is worth noting that 70% of installers and customers who opt for smart thermal stores do so based on the assumption that the installation process is similar to that of conventional thermal stores. However, if the installation process becomes too complex or the costs too high, this percentage could decrease.

Commercialisation plan

Market analysis and engagement with the current SAP contractor, BRE, sought to understand the applicability of the PCM and TCS thermal storage solutions. The key findings and outcome of the research is outlined below:

Findings in relation to the TCS system

1 TCS is likely to be more applicable to the commercial/industrial sector where the system performance in terms of volumetric efficiency scales more favourably for larger demand requirements.

2 For domestic systems, whilst there is an uplift in volumetric energy storage density compared with sensible heat solutions (like stratified hot water), the TCS system is overly cumbersome due to:

   a. The poor heat transfer associated with the material which necessitates a large surface area within the device (offsetting inherent volumetric gains derived from the substrate itself).
   b. The amount of ancillary equipment to the thermal store which further offsets the gains from the substrate.

3 In general, new system installations into the new build and retrofit domestic markets are heavily regulated, TCS systems are punished due to poor performance within the

Standard Assessment Protocol (SAP) which deliver low EPC scores. The EPC penalty occurs because SAP models the heat battery under a standard electricity tariff, without recognising or accounting for the benefits of load shifting and other flexibility services that a thermal store can offer. This will penalise local authorities and new build developers who might consider the technology. While the SAP model does include PV and batteries with similar logic, and the weaknesses of RTE and heat loss negatively impact the thermal store's SAP score, it is still important to capture the broader energy system-level benefits that thermal stores can provide. Challenges such as fire regulations and cost have also hindered the widespread adoption of battery energy storage systems. For example, PAS 63100:2024 specifically states that solar batteries shall not be installed in "voids, roof spaces, or lofts," which could make a thermal store a more suitable solution for some indoor installations than batteries. Furthermore, a study by the University of Sheffield showed that current PCM storage has a lower embodied carbon footprint than battery technologies. Given these considerations, Mixergy is actively engaging with BRE and other stakeholders to ensure that thermal stores with smart controls are recognised in the new SAP model.

4 Whilst there are ongoing policy discussions around the recognition of heat-batteries, there is ambiguity around the extent to which these solutions will become eligible for funded retrofit measures. Heat batteries are an eligible measure for Warm Homes: Social Housing Fund once they can be modelled in SAP and can be MCS certified. A decision on funding for heat batteries under the Boiler Upgrade Scheme (BUS) was being awaited at the time of publication of this report.

5 Fundamentally, TCS systems are most likely to deliver a benefit in commercial/industrial applications where there is:

   a. A high demand for heat in a concentrated production, high occupancy environment.
   b. A large amount of local embedded generation (typically roof mounted solar PV arrays) which would encounter a grid constraint, thereby creating an incentive to consume energy on site.

Findings in relation to the PCM system

1 Phase Change Materials, operating around temperatures that are amenable to heat-pumps, offer a more promising proposition to the domestic market compared with TCS systems.

2 During this project, it was found that operational savings of up to 44% could be derived through tariff arbitrage savings compared to the gas boiler system. However, it is worthwhile considering the heavy capital investment required for the heat pump and thermal store installation.

3 Whilst the operational savings are welcome, the baseline we were comparing to involved room emitters (radiators) that operated at a higher than nominal temperature because:

a. A high temperature heat-pump was installed.

b. This high temperature heat pump had to run at a higher than nominal temperature to activate the PCM (temperature ~55°C).

c. The emitters (radiators) had not been uprated since they were running at a sufficiently high temperature.

This observation suggests that it would be better to first invest in larger radiators to achieve a lower flow temperature and a higher COP rather than develop a system specification centred around a high temperature PCM based thermal store

4 Whilst an OPEX improvement has been established, it is marginal considering that new build developers and social housing providers operate in a ‘lowest cost of compliance’ environment within the SAP regulatory framework. Their objective is to hit a carbon, energy and operational cost threshold whilst spending the minimum amount to maximise their margins. Any PCM based thermal store delivering an uplift in the SAP score will have to be cost effective against alternative measures such as:

a. Adding an additional solar PV array.

b. Fitting wastewater heat recovery in a shower unit.

c. Putting additional insulation in a wall cavity.

The marginal cost benefits demonstrated might struggle to compete against alternative means of improving the SAP score.

New build developers are, however, interested in load shifting with flexible heating technologies due to network constraints which are delaying build programmes. Whilst electric battery technologies do benefit from the leveraging effect of the heat-pump, a combination of fire regulations and cost are inhibiting their uptake in new build.

5 Another argument in favour of a PCM thermal store over batteries centres around embodied carbon. Whilst not in place today, the direction of travel for new build and social housing is driving towards the specification of products which are responsible for lower carbon emissions in their production. Given the complex supply chain associated with lithium-ion battery solutions today, the material intensity and environmental overhead, PCM systems could offer a compelling alternative.

Next steps around commercialisation based on findings

The next steps for the PCM system are:

- Undertake a deeper techno-economic comparison between a PCM thermal store operating in tandem with a high temperature heat pump against a low system temperature design with larger radiators. Even though these two measures are not mutually exclusive, it helps understand the relative OPEX/CAPEX trade-off between the two solutions.

- Explore a wider range of PCM materials which could operate at different temperatures within the same system. For instance, 55°C and above within the hot water store and 40°C within the central heating volumiser.
- Examine the range of lowest cost of compliance solutions already acknowledged on the Standard Assessment Protocol (SAP) and registered through the Product Characteristics Database (PCDB) against which a PCM based thermal store solution will have to compete to ascertain the final BOM cost. Competing solution analysis to include: Incremental additions of solar PV, incremental additions of insulation, or installation of wastewater heat recovery systems.

The next steps for the TCS system are:

- Explore low grade industrial heat demand sectors pursued by businesses.
- For the commercial sector, undertake a techno-economic feasibility study around the optimum ratio of building demand to plant room size to ascertain the applicability of the TCS solution.
- Undertake a Design for Manufacture (DfM) study to examine the potential around reducing the ancillary component sizing alongside store size measurements.

Commercial development: PCM onward path

The commercial case for TCS storage in a residential setting is particularly challenging given current policy drivers and the relative maturity of the technology. However, PCM-based thermal storage represents a technically viable solution that may also reach commercial viability if costs can be shown to be competitive with competing technologies and if policy-based disincentives to uptake of storage technologies can be addressed.

Future PCM deployment: active buffer configuration

Figure 81 presents an alternative hydraulic design for incorporating the developed PCM store into a standard heat pump installation. The intention is that the PCM system could be implemented as a drop-in replacement for a passive hot water buffer, with the latter commonly installed to allow differing flow rates in the primary (heat pump) and secondary (space heating) circuits, in addition to overcoming issues with short cycling of the heat pump. A key distinction is that the proposed system would be operated in an active fashion in response to price signals (TOUTs and flexibility services).

The design is based upon that for a 2-pipe buffer tank, with charging and discharging of the store control by the relative flow rates through pumps P1 (primary circuit) and P2 (secondary circuit). Charging occurs when flow through P1 exceeds that through P2, with the excess hot water flow from the heat source passing into the store. When flow through P2 exceeds that through P1 discharging occurs, with water drawn from the 'hot' outlet of the store and passing to the sink.

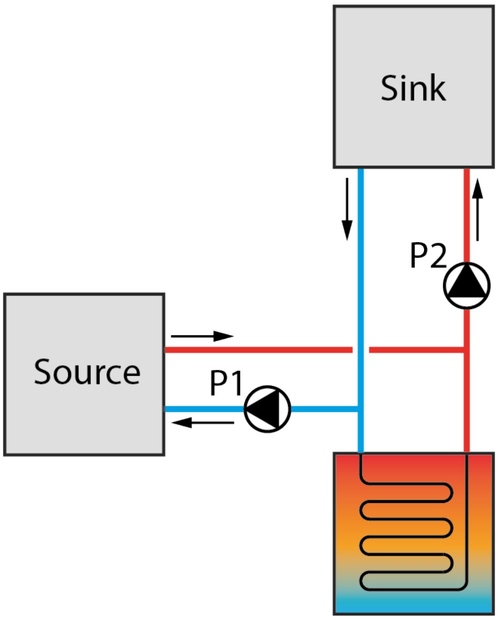

Figure 81: Schematic of 2-pipe active buffering design.

Such a setup has numerous advantageous features over the current designs:

- The flow direction through the store may be reversed between charge and discharge as required, without needing dedicated valve work.
- It is possible to simultaneously charge the store and provide hot water to the sink; it is similarly possible to provide energy to the sink using a mix of flows from the source and the store.
- The design is very simple from a hydraulic perspective, without the need for any actuated valve work, pumps or heat exchangers beyond those required for a standard heat pump installation.
- Pipe runs (and thus thermal losses) are minimised through placing the store between the source and sink. Bringing the store close to the source would be expected to be particularly beneficial; reducing thermal losses here may allow lower flow temperatures during charging, aiding COPs.

It is noted that the pumps must be specified such that they can overcome the pressure loss across the PCM store. It is also noted that attention would need to be paid to flow and return temperatures within both circuits as part of the applied control strategy, such that charging/discharging of the store may be appropriately managed.

It is expected that such a setup would enable RTEs for the system to approach those observed in laboratory conditions (85-95%, as reported in the Laboratory for Verification and Validation (LVV) section of the PCM work). It would also enable the capital costs of the system to be minimised. These expectations form the basis of the cost analyses that follow.

Space heat cost saving potential versus a hot water store

A key metric for any domestically focused energy storage system is its ability to shift demand away from periods of constrained supply. In the UK, these constraints present a particular challenge during the 4pm to 7pm period on weekdays, where industrial demand overlaps with a period of high domestic energy use.

This section provides a brief analysis of the quantity of space heating load that may be shifted out of the peak period using the proposed PCM active buffering approach, and an analysis of the cost savings per cycle that may be returned as current market prices. The cost of providing this heat using a hot water tank – again set up in an active buffering configuration – is taken as a baseline. The focus of the analysis is space heating, given:

- The much larger annual demands associated with SH loads. DHW accounted for 19% of overall domestic heat demand in 2023, with SH accounting for the remainder[1].
- The fact this load is less amenable to temporal shifting. Peak periods for UK energy usage (typically 4pm and 7pm on weekdays) coincide with typical periods for domestic space heating demand. It has been shown that thermal mass activation – pre-heating the dwelling using a heat pump in advance of the peak period – can make a useful contribution to reducing peak demand. However, there are constraints on the amount of energy that can be shifted without impacting thermal comfort using this approach, and storage durations are short, given the high thermal losses of buildings; the stored energy must in effect be used immediately.

The analysis proceeds by considering the relative capacities that may be shifted via each method. By considering generation and storage efficiencies alongside available tariffs costs, the cost savings per cycle for each technology may be calculated and compared.

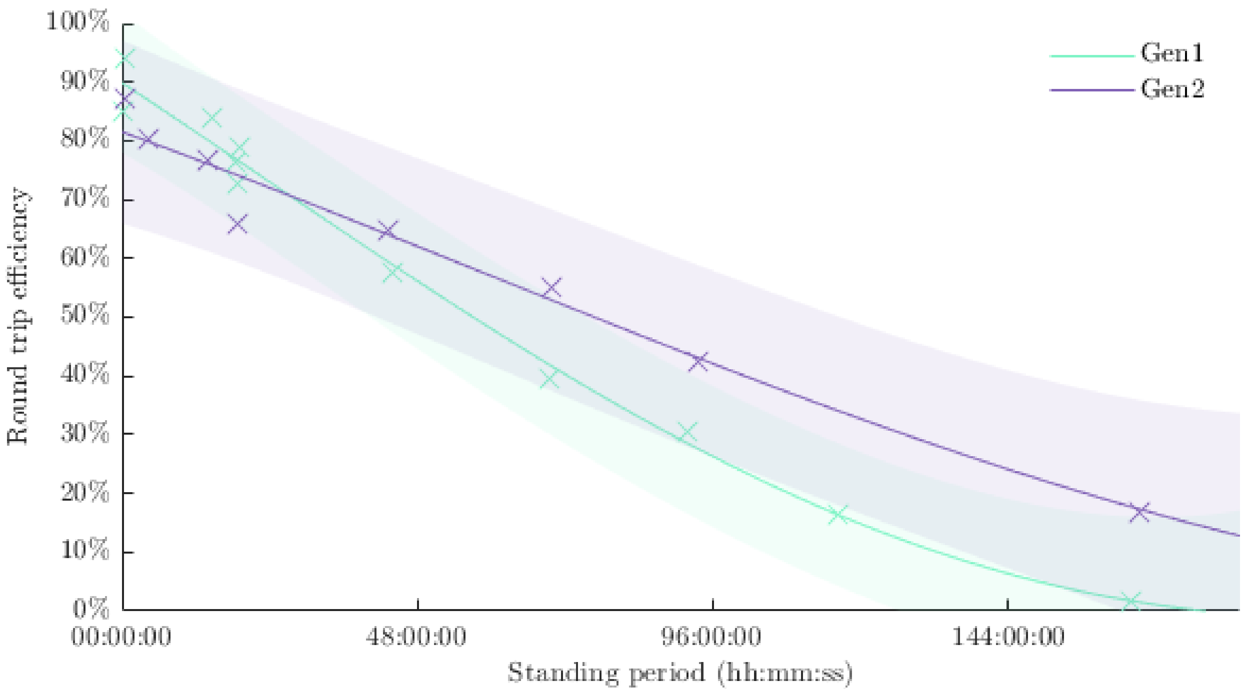

Figure 82: Re-presentation of Figure 28 - RTE values for Gen 1 and Gen 2 PCM stores.

[1] https://www.gov.uk/government/publications/domestic-hot-water-use-in-the-uk

In this analysis, it is assumed that energy is stored in the active buffer tank by raising the temperature of the storage material (whether water or PCM) by 20°C from a given datum. For the space heating use case being considered, this datum would be the return temperature from the SH circuit. The capacity of the water store is based on a standard 50 litre buffer tank; the external dimensions of such stores are closely comparable to those of the developed PCM stores, although in a cylindrical rather than cuboidal form factor. For the PCM store, a value of 3.44kWh is adopted. This is based on the theoretical analysis conducted by the CREST team for a single Gen 2 unit operating over a 20°C range, with these values corroborated by experimental data gathered at the LVV, LCL and CREST.

The heat pump COP is based on the median seasonal performance factor (SPF) for ASHPs returned by the Electrification of Heat Demonstration project[2] (SPF_{H4} = 2.78, where the H4 subscript denotes that the COP values included energy usage for backup heaters and auxiliary equipment such as hydraulic pumps associated with the heat pump). It should be noted that this SPF value encompasses both SH and DHW demands; the COP when meeting SH demand alone would be expected to be higher. Observed RTEs from lab testing of the two generations of PCM store are re-presented in Figure 82. An RTE value of 85% is adopted for the no standing period case, with an RTE of 75% adopted for a longer duration (12-hour) standing period. For simplicity of comparison, it is assumed that these losses are the same for both storage types. The resulting efficiencies are shown in Table 7.

Table 7. Efficiencies and costs of PCM and hot water stores in active buffering configuration

	Water store (no standing period)	PCM store (no standing period)	Water store (12hr standing period)	PCM store (12hr standing period)
Capacity (kWh)	1.34	3.44	1.34	3.44
COP	2.78	2.78	2.78	2.78
RTE	0.85	0.85	0.75	0.75
Overall efficiency	2.36	2.36	2.09	2.09
Standard price (p/kWh)	24.9	24.9	24.9	24.9
Off peak price (p/kWh)	14.0	14.0	7.0	7.0
Saving (p/cycle)	4.0	10.4	7.5	19.2

[2] https://es.catapult.org.uk/project/electrification-of-heat-demonstration-project

The final row of Table 7 provides an indication of the savings per cycle that may be achieved by adopting each of the solutions alongside an appropriate tariff. The saving per cycle is calculated as follows:

$$Cost_{saved} = Cost_{direct} - Cost_{store} = \frac{P_{standard} \times Capacity}{COP} - \frac{P_{offpeak} \times Capacity}{COP \times RTE}$$

For the East Midlands region in February 2025, the Energy Price Cap rate for electricity was 24.86 pence per kWh. However, a range of TOUTs that encouraged load shifting were available at this time. Two key tariff types are highlighted below:

- Heat pump tariffs offering off-peak periods throughout the day, for example 4am to 7am, 1pm to 4pm and 10pm to 12am (midnight). The Octopus Cosy tariff offered rates of approximately 14 pence per kWh during this period. These tariffs would be appropriate to the “no standing period” cases, with the store charged immediately before the standard or peak period and then discharged during this period.
- EV-focused tariffs offering highly discounted overnight rates. Off peak rates of <8 pence per kWh for periods of 4 to 6 hours were widely available during this period, with the Octopus Intelligent Go tariff, which offered a rate of 7 pence per kWh from 10:30pm to 5:30am used for illustration. These tariffs would be appropriate to the “12 hour standing period” cases, potentially enabling heat generated overnight to be discharged during the 4pm to 7pm peak period.

The conclusion that may be drawn from Figure 83 is that the cost saving achieved by cycling the PCM unit once per day to cover the 4pm to 7pm period appears comparatively small. If cycled in full once per day during a 180-day heating season, the total cost saving versus direct generation using a standard tariff would be £18.69pa for the no standing period (Cosy) case and £34.58pa for the 12-hour standing period (Intelligent Go) case. Savings improve to £56.06pa if the unit is cycled three times per day with no standing period, consistent with the goals of the Octopus Cosy tariff. However, two key points are highlighted:

- This additional flexibility is delivered by swapping what is typically a required component (a passive buffer store) with an active PCM, without substantial change to space requirements or installation complexity.
- The analysis is based on current (as of February 2025) retail tariffs. These are designed to incentivise consumer-led flexibility but do not directly reflect the underlying constraint costs incurred during peak times (principally 4pm to 7pm on working days).

Electrification of heat at scale has the potential to add to balancing challenges - and thus costs - during peak times. This motivates consideration of the extent to which space heating loads can be shifted out of the peak period by incorporating active buffering.

Space heat load shifting potential

Figure 83 seeks to place the load shifting capacities of three storage configurations into context. These configurations are the 50 litre hot water tank and single PCM store detailed in Table 7, and a three-unit PCM system (total capacity 10.32kWh when operating over a 20°C range). Also shown in Figure 83 is the energy required to meet 3 hours of steady state space heating demand across a range of heat loss coefficients (HLCs) and external ambient temperatures. An internal temperature of 20.5°C is assumed. The range of heat loss coefficients chosen for illustration reflects expected heat losses for moderately well insulated buildings based on SAP assessments using English Housing Survey data.

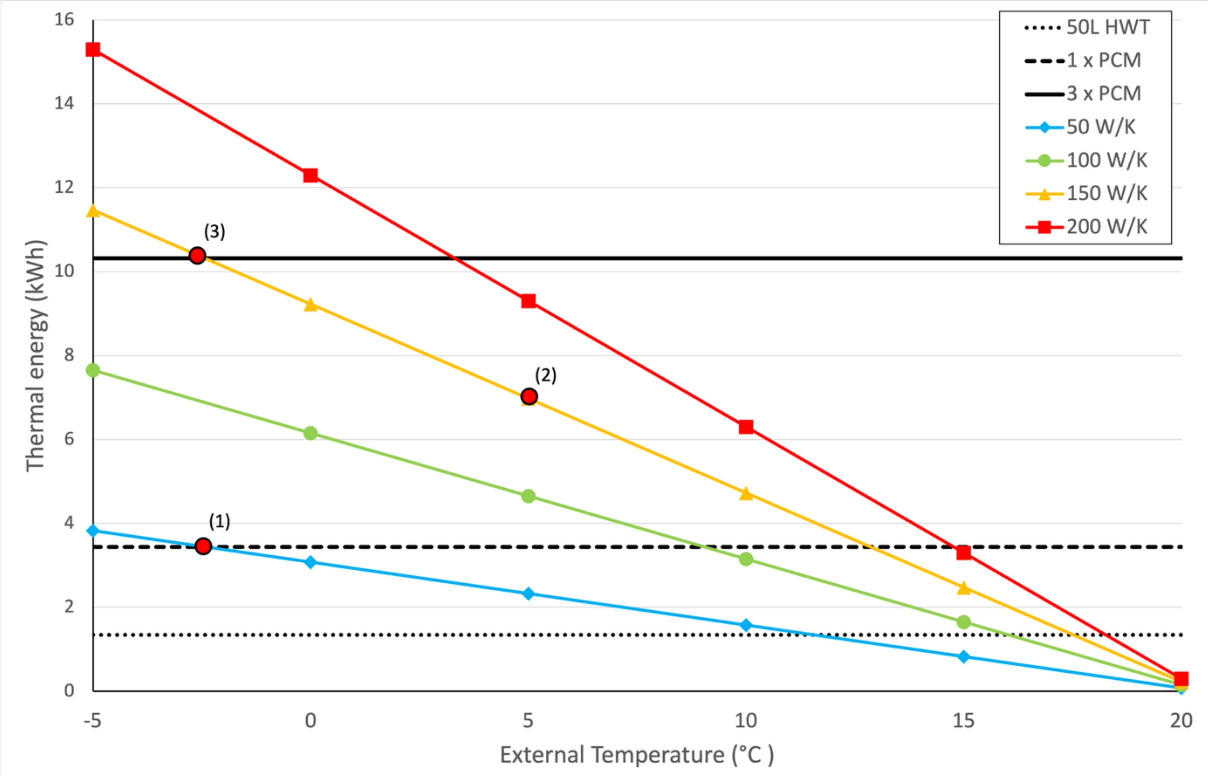

Figure 83. Comparison of (i) the thermal capacity of a set of storage configurations and (ii) the energy required for 3 hours of space heating across a range of heat loss coefficients. An internal temperature of 20.5°C is assumed.

Using the three points highlighted in Figure 83 for illustration, it can be observed that:

1. The single PCM store would have sufficient capacity to completely meet the required heating load for a highly insulated (50 W/K HLC) building at an external temperature of around -2.5°C.
2. Considering a more typical use case, around 50% of the steady state load for a moderately well insulated (150 W/K HLC) building could be met by a single store at an external temperature of 5°C.
3. If space were available for the 3-unit PCM store demonstrated within the project, the full steady state load for the same moderately insulated building (150 W/K HLC) could be covered by the buffer unit down to an external temperature of around -2.5°C.

Outcomes of the brief analysis in this section are summarised below:

- Combining an ASHP with a PCM-based thermal store and making use of currently available TOUTs has the potential to provide a moderate level of cost saving versus meeting these demands directly via the ASHP.

- The inclusion of discrete thermal storage removes the constraints imposed by the need to maintain thermal comfort for the ASHP-only case.
- The use of a PCM store with an appropriately specified phase change temperature would allow approximately 2.5 times the amount of thermal energy to be stored in a given volume compared with equivalent hot water storage device. This increases the load that may be shifted without substantially increasing change space requirements or installation complexity.
- Larger scale PCM stores could have a substantial impact on peak time (4pm to 7pm) energy use for space heating; where space permits, there is potential to cover the full space heating load for a moderately well insulated property at external temperatures <0°C.
- Key to achieving these outcomes in practice will be maintaining – or improving upon – the SPFs reported by the Electrification of Heat project. For the proposed active buffer configuration of the PCM store, this will primarily be achieved through minimising the gap between the required store charging temperature and the flow temperature of the heating load.

Project conclusions

The aim was to progress the technical readiness of two novel advanced thermal storage technologies to TRL 7 through successful demonstration in an operational environment. Substantial progress has been made against this aim, with the PCM stores having been trialled over an extended period during the 2024/25 winter heating season. Installation and operation of the TCS stores in both a domestic property and connected to a DHN has also been demonstrated, although for a shorter trial period.

The key project outcomes are briefly summarised below:

- The design and manufacture of multiple generations of both PCM and TCS storage devices was successfully completed by CREST, with a substantial amount of initial characterisation testing also conducted.
- Systems were successfully installed into all five trial locations.
- New experimental rigs for testing of storage units in controlled environmental conditions were developed and implemented at the LVV, and a new domestic energy system testbed deployed in the LCL. These have enabled detailed characterisation of the manufactured storage units both in idealised conditions (TCS and PCM) and at systems-level (PCM) and have provided support for the in-home trials.
- New control hardware and software for both the PCM and TCS stores was successfully developed and deployed. This spanned both single-dwelling and multi-dwelling control, enabling exploration of aggregated control of distributed resources for grid benefit.
- Extensive testing of the PCM stores in realistic environments was conducted at CEH, building a greater understanding of real-world performance and enabling numerous practical challenges relating to installation, control and interoperability with other low-carbon technologies to be identified and addressed.
- Advances were made in online State of Charge (SoC) techniques for PCM stores spanning both physics-informed system identification and exploration of novel sensing methods. The outputs of these approaches have been used to support ongoing development of model predictive control (MPC) methodologies appropriate to the technology.
- A greater understanding of the commercial case for the two technologies has been developed through extensive stakeholder engagement and market analysis, supported by the outcomes from the technical work streams.

Key technical conclusions relating to the thermal storage systems and associated controls are briefly summarised below:

- PCM stores have been designed, manufactured, characterised under lab conditions and installed and tested at all planned trial sites. Characterisation tests have validated that when charged to 70°C, over 10kWh of heat may be delivered at temperatures of over

50°C, thus being suitable for direct use for either domestic hot water or low temperature space heating.

- The PCM stores have been demonstrated to be effective in enabling load shifting between peak and off-peak periods in real-world environments. However, a key finding of the project is that there may be scope to substantially simplify the hydraulic integration of the PCM stores with the domestic heating system. This has the potential to achieve simplification of the required control approach, overcome many of the challenges around heat pump interoperability, and reduce implementation costs by drastically rationalising required ancillaries (e.g. pumps and valves). Similarly, there may be scope to improve overall system COPs by considering PCMs with lower phase change temperatures, enabling more optimal use of heat pumps when charging the stores.
- First-of-a-kind demonstration of a full-scale TCS device intended for use within a domestic setting has been achieved, with demonstration of this device when installed on both a district heat network and connected to a domestic property. Successful charging and discharging of the technology was demonstrated in both installations, in addition to successful demonstration in laboratory conditions at UoS and CREST.
- There remains a great deal of scope for further improvement of TCS system performance. The large thermal mass of the Gen 1 systems, combined with temperature and pressure restrictions put in place to comply with PSSR, had a significant effect upon both charging and discharging efficiency. The Gen 2 design represented a step forward with regard to thermal mass, with the potential to achieve further substantial reductions with an aluminium enclosure as proposed as an option for the Gen 3 design. Similarly, the charging temperature could be increased by seeking certification to operate at higher temperatures than the 110°C permissible under PSSR.

Key commercial conclusions are summarised below:

- Demonstrating successful operation at full-scale in real-world environments represents a substantial step forward for the TCS technology. However, it was concluded that the TCS proposition remains some way from commercial viability, and particularly so for domestic application. This conclusion was drawn based upon a number of factors including the form factors, system, cost levels and performance parameters. Several potential non-domestic use cases were identified, and it remains feasible that this technology could reach viability as a domestic solution with significant further development and optimisation.
- The case for the PCM proposition is more promising, although the cost and relative complexity of the current implementation may place it at a disadvantage versus other technologies in SAP.
- A simplified active buffering implementation has the potential to aid commercial viability through improving system performance and minimising capital and operational costs. It has been shown that successfully implementing such an approach has the potential to make a substantial contribution to addressing space heating loads during the peak 4-7pm weekday period.

Appendix: Knowledge and dissemination activities

Knowledge and dissemination activities undertaken during the project sought to raise awareness of the technologies, their potential impact, and to support commercialisation.

One-to-one and group briefing sessions. The project team undertook proactive engagement with a diverse range of stakeholders, including consultants, catapult organisations, housing providers, research bodies, local authorities, industry partners, and potential collaborators.

Academic papers. The project contributed publications directly relevant to the project's core innovations. Two journal papers had been published at project conclusions, with further publications in preparation:

Conferences. The project was able to share research outcomes to a broad and relevant audience through a diverse range of events.

Demonstrations. Events held at both the University of Sheffield's low carbon research lab and the real-life homes at the University of Nottingham creative energy homes campus provided excellent opportunities for stakeholders to see the technology installed and engage directly with the research team.

A broad range of attendees were hosted, including SME plumbing companies, universities, local authorities, housing groups, consultants, manufacturers, and energy utility providers. Engagement with them enabled the project team to explore development opportunities, identify potential research collaborations, discuss interoperability issues, and identify use cases. On site engagement also resulted in several follow up discussions, including further exploration of the technology potential within affordable net-zero heating within the social housing stock and further development to address the ASHP interoperability issues.

Ongoing access to the Low Carbon Lab is also available beyond the project's lifespan to further enhance the long-term impact of the project.

Access can be arranged by contacting the School of Mechanical, Aerospace and Civil Engineering at the University of Sheffield.

If you need a version of this document in a more accessible format, please email alt.formats@energysecurity.gov.uk. Please tell us what format you need. It will help us if you say what assistive technology you use.