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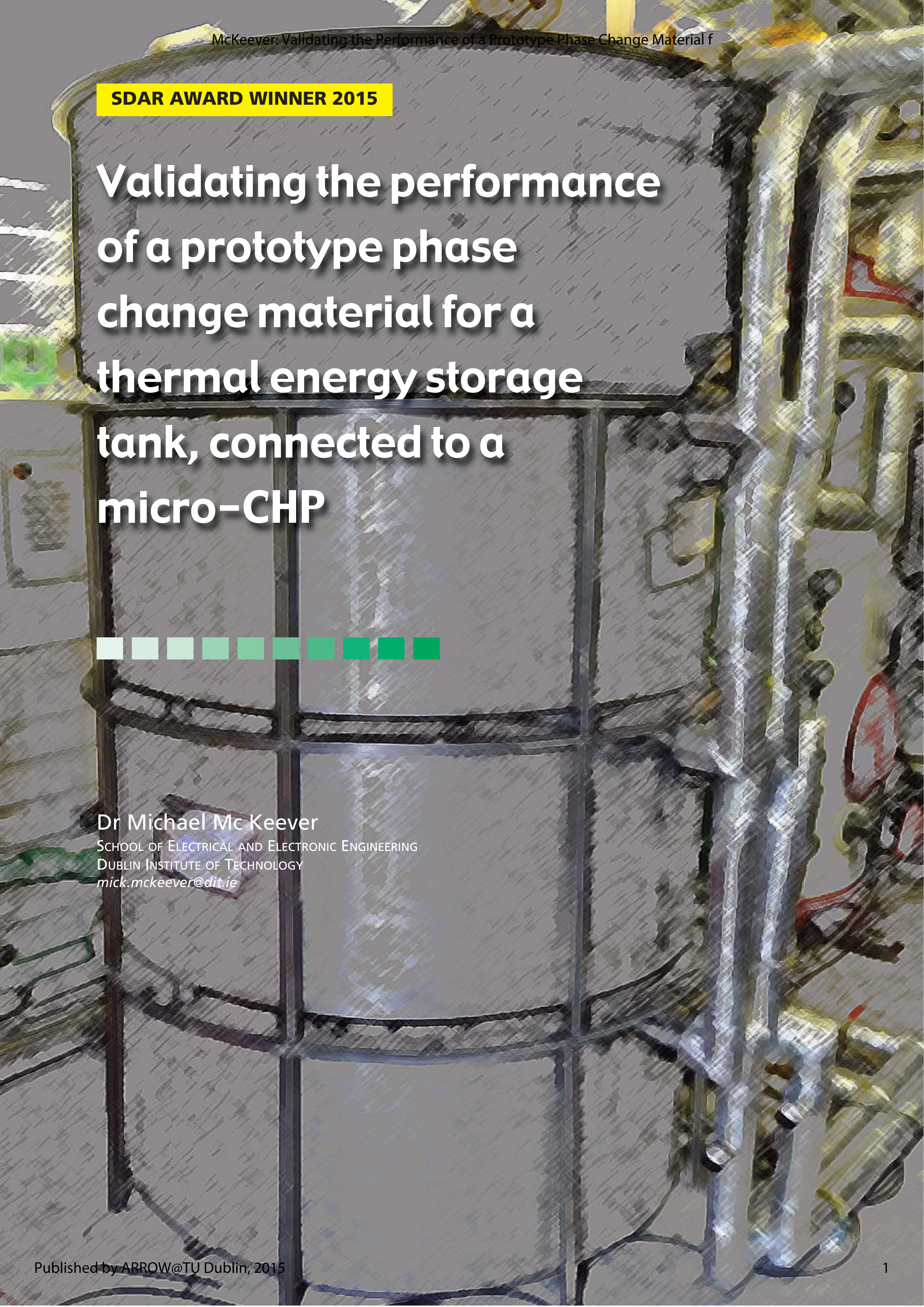
Mick McKeever
Technological University Dublin, mick.mckeever@tudublin.ie



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Validating the performance of a prototype phase change material for a thermal energy storage tank, connected to a micro-CHP

Dr Michael Mc Keever
School of Electrical and Electronic Engineering
Dublin Institute of Technology
mick.mckeever@dit.ie

Abstract

This paper describes the performance testing of a 2000-litre phase change material used in a Thermal Energy Storage (PCM-TES) demonstrator unit invented in DIT's Dublin Energy Lab and installed in an office building in Cork in 2014. The PCM-TES is connected to a Micro-CHP unit and stores waste heat from the CHP at evening peak tariff periods when the building heating loads are lowest. The CHP is also connected to a 2000-litre water tank allowing direct comparison of the energy storage capacities and performances of both storage systems. Charging results presented show that the PCM-TES holds 6.5 times more heat for the same plant room footprint, allowing the CHP to run continuously during peak periods and producing a better overall electrical/ thermal efficiency. Discharging results show how the PCM-TES stored energy can be used to pre-heat the building heating system early in the morning, shifting CHP thermal demand to align better with the day rate electrical tariff period. The PCM-TES eliminates the need for back-up gas boilers to be used for the early morning heat demand peak. A discussion of PCM-TES benefits over a water-based TES is supported and presented here.

Key words:
Phase change materials, latent heat storage, thermal storage and CHP

Glossary:

PCM	*Phase change material*
TES	*Thermal energy store*
CHP	*Combined heat and power*
NPV	*Net present value*
SPP	*Simple payback period*
ROI	*Return on investment*

1. Introduction

Identifying the economic advantages of installing micro-CHP in buildings requires a techno-economic analysis over the full life-cycle of the system. Financial decision makers have to be convinced that a proposed plant room installation has a reasonable payback and is a sustainable acceptable risk investment. This argument can be made using estimated up-front capital costs, running costs and disposal costs, in calculation of Net Present Value (NPV), Simple Payback Period (SPP) or Return on Investment (ROI) analysis. The most difficult costs to predict are the fuel consumption and maintenance costs of running the equipment over its lifespan. Techno-economic results are always compared to other benchmark technology solutions on the market. In retrofitting, the availability of plant room space and the footprint of the equipment must not be overlooked.

The argument for CHP is that the electrical power can be exported at a profit, but this only makes economic sense if the heat can be used directly or stored for later use. The heat energy needs to be used to make CHP a viable and sustainable solution. This requires storage as the heat demand profiles do not necessarily coincide with high electric tariff periods. Thermal energy storage allows the CHP to export electrical power at peak electrical demand periods and to release heat when building thermal demands are high during low electrical tariff periods. This has traditionally been implemented using Sensible Heat Thermal Energy Store (SH-TES) water tanks that store energy by raising the temperature of water inside the tank. This solution is low risk and the benchmark used to compare thermal energy storage solutions. However, these SH-TES units are large, often occupying significant plant room floor space or, if very large, they may require planning permission when installed outside the building.

A new 500-litre Phase Change Materials Thermal Energy Store (PCM-TES) was developed at the Dublin Institute of Technology. The PCM-TES was designed to store six times the energy storage capacity of a SH-TES operating on a 5°C differential temperature. A building heated by a micro-CHP with a 2000-litre SH-TES was selected as an ideal demonstration site. A 2000-litre PCM-TES (4 x 500-litre) was retrofitted in parallel to the 2000-litre SH-TES to enable comparative testing of both energy stores. The objective was to produce data suitable for a techno-economic analysis of the PCM-TES system.

2. Background

PCM is a material that absorbs latent energy as heat when it melts and releases this latent heat back when solidifying[1][2]. The temperature of melting and solidifying are separated by a few degrees and high quantities of heat can be stored over small differential temperatures (Delta-T)[3]. An example of this is a 1kg of RT70HC wax[4] which melts and solidifies in the temperature range 69°C to 71°C and stores 64Wh/kg. A corresponding 1kg of water over the same temperature range stores only 2.3Wh/kg. In practice, the energy storage density ratio between PCM and water is lower[5]. If the operating temperature range was increased to 66°C to 71°C, the energy density ratio would drop to around 9:1 when comparing PCM to water on a volumetric basis.

PCM absorbs heat more slowly than water and large blocks of PCM do not have the dynamic response times required by building heating systems to meet load fluctuations. The thermal conductivity of wax-based PCM is 0.2W/mK compared to 0.58W/mK for water. Charging and discharging response times are proportional to the ratio of the PCM volume to surface area(6).

The low thermal conductivity problem with PCM can be overcome by distributing the heat source and heat sink inside the PCM using pipes, fins and plates. This increases the heat transfer rates by increasing the heat exchange surface area but, as a consequence, it reduces the quantity of PCM for a fixed volume. A significant PCM-TES design challenge is to find the correct compromise between energy storage density and heat response rates to meet heat demand peaks and troughs(7).

This research set out to develop and evaluate a novel PCM-TES design for use in buildings. The PCM-TES demonstrator unit is installed in the CIT Nimbus building plant room and coupled to a micro-CHP unit(8). The focus of this paper is not on the internal design of the PCM-TES unit but on a comparative study of the performance of this system compared to an identical sized water tank operating in a live building. The test results on the PCM-TES unit are presented to validate the system design concept and performance when coupled to a micro-CHP.

3. The PCM-TES demonstrator tank

The PCM-TES prototype uses four 500-litre metallic tanks, each with two suitably-shaped hydraulic coils and inner space filled with PCM. A picture of one tank is shown in Figure 1 with the lid partially removed, revealing the internal PCM and two heat transfer coils. The inlet piping of the system at the front shows the piping terminals for each coil.

Figure 1: Prototype 500-litre PCM-TES unit.

The PCM-TES unit operates as follows in the demonstrator. The primary coil is used to supply thermal output from the micro-CHP into the PCM-TES. The PCM-TES unit discharges its energy through the secondary coil. This allows the primary and secondary circuits to be operated separately so the unit may charge and discharge

Figure 2: PCM-TES installation during commissioning (only top unit shown insulated).

simultaneously or independently as required by the CHP controller and BMS system. The thermal storage capacity of a 500-litre unit is 29kWh for a delta-T of 5°C across the primary coil. The PCM used in this demonstrator is a wax-based commercial PCM that is non-corrosive and has a life of over 10,000 solid-liquid charging cycles. Unlike salt-hydrate PCM materials, wax PCM does not suffer from under-cooling, or permanent material segregation, and has a pH close to 7(9). The four unit demonstrator is shown in Figure 2.

This gives a total capacity of 126 kWh of storage for a delta-T of 20°C across each unit connected in series. Two PCM materials are used. The top unit is filled with a PCM with a melt temperature in the range 80°C to 82°C, while the other three units are filled with a PCM that melts in the range 68°C to 70°C. The 2000-litre PCM-TES allows direct comparison between the PCM-TES technology and the 2000-litre SH-TES installed as part of the original plant room CHP installation.

4. The demonstrator site installation and operation

The Micro-CHP unit is a natural gas-fired Sokratherm GG50 with a 90°C/70°C thermal circuit(10). The CHP installation is controlled by a PLC-based SCADA system allowing set point control of both thermal and electrical outputs.

The SCADA system has full integration with the BMS system that

Figure 3: Plant room showing the CHP, PCM tanks and sensible water tank.

controls the energy requirements of the building. The initial plant room design incorporated a 2000-litre Sensible Heat Thermal Energy Storage tank (SH-TES). Figure 3 shows the SH-TES (red and white in the background), the CHP unit and the PCM tank during its commissioning. A simplified process schematic of the heating system is shown in Figure 4 for the PCM tank only. The sensible tank operates in parallel with the PCM tank connections (not shown in Figure 4). The CHP-PCM-TES heating circuit system consists of two parts, the primary charging loop operating on a 90°C/70°C supply heat from the CHP and return line operating on a 70°C/50°C loop. The thermal output of the CHP is controlled by varying flow through the VSD pump (P01) to maintain a 90°C CHP output temperature. The CHP trips out if the return temperature exceeds 75°C for a period of time.

The secondary side of the PCM-TES is connected to the building system header and return pipework. This is controlled by a variable speed pump (P02) drawing water from the return manifold which is heated in the PCM tank before discharge into the building heating header manifold.

The heating system also includes two back-up gas-fired boilers which are activated if the header return temperature drops below 62.5°C. Gas consumption of the boilers in the morning was in the region of 70kWh during the heating season.

The heating system operates as follows under BMS control. At 7am the BMS calls for heat and the CHP starts. Normally the large thermal load on the return manifold causes the gas fired boilers to both activate and complement the CHP. When temperatures stabilise, the CHP operates alone and supplies heat to the building. When the thermal demand drops, the CHP charges the SH-TES and shuts down when the SH-TES exceeds 85°C. The CHP kicks in again when tank temperatures drop below 74°C. During peak tariff periods the CHP exports electrical power. However, the heat demand of the building is low at this time and excess heat is dumped to air to prevent the CHP tripping out on high return temperature.

The retrofitting of the PCM-TES to the CHP was carried out to produce real building data to answer three key research questions:

1. How much energy could the PCM-TES store when operating in a real building driven by a micro-CHP?
2. How long could the PCM-TES extend the operation of the CHP without dumping heat to air?
3. What percentage of the operation of the gas fired boilers could be eliminated in the morning by discharging the PCM-TES prior to 7am?

Validating the performance of the prototype PCM-TES tank connected to a Micro-CHP is essential to demonstrating system performance. This provides data to allow cost benefit analysis of PCM-TES for other installations.

5. Results

The testing scenario for the PCM-TES and SH-TES was identical. The CHP thermal output was used to charge one tank at a time, with no heat being delivered to the building during charging. This helped to make the PCM-TES and SH-TES tests comparable by removing the variable building loads affecting test results. As a consequence, the CHP outputs were turned down to 50% operation to replicate the normal charging process with the building load taking the other 50% output. CHP thermal output in the range 20kW to 25kW thermal and electrical output varied between 20kW to 30kW.

During the discharging both systems were allowed to discharge their energy into the building manifold under the same conditions. This occurred when the manifold return temperature was 60°C.

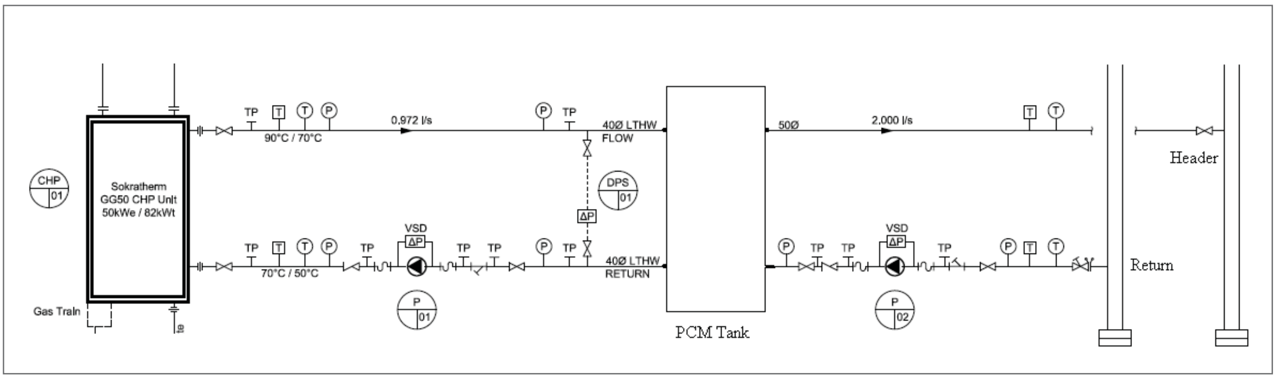

Figure 4: Process and instrumentation drawing for the PCM tank demonstrator site.

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6. CPH thermal operation during charging

The first test conducted was the charging of the SH-TES as shown in Figure 5. The heating control system kicks in when the top temperature of the SH-TES drops below 75°C. Stratification in the tank can clearly be seen as the bottom temperature in the tank is 55°C. The charging takes 17 minutes and the total energy stored by the SH-TES is 13.5kWh over this period. The CHP stops when the upper temperature limit of the top temperature is exceeded at 86°C. It should be noted that the lowest temperature in the SH-TES is 73°C, showing large temperature stratification within the tank. This is significant when discharging the tank into the header as the return temperature is below the 60°C set point start of the boilers.

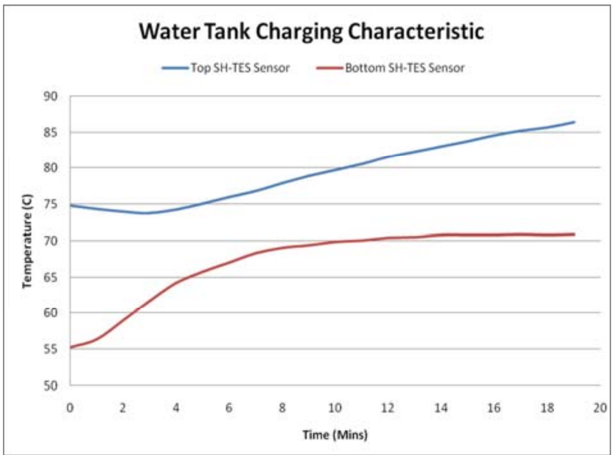

Figure 5: Single charge of the SH-TES from 75°C to 85°C.

During early morning heating of the building, the PCM-TES is allowed to discharge to below 60°C into the header manifold which is the cut-in set-point for the back-up boilers. In this set-up it takes 200 minutes to fully charge the PCM-TES as can be seen in Figure 6.

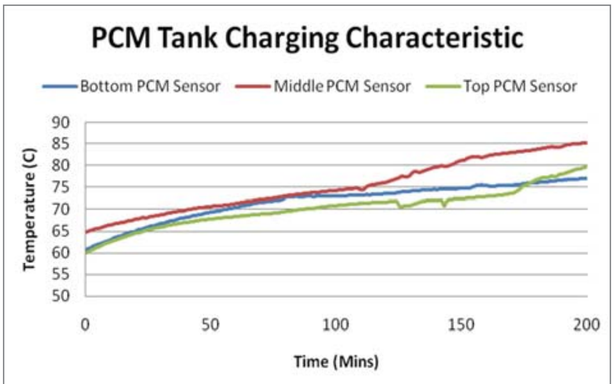

Figure 6: Single charge of the PCM-TES from 60°C to 85°C.

Energy total stored by the PCM store is shown in Table 1 for a full charge cycle of the PCM-TES between 60°C and 85°C which is defined by the BMS control system. The PCM inside all the units heat above their melt temperatures and the control system shuts down the CHP when the highest temperature reaches 85°C.

Temperature Rise °C	PCM Energy Stored kWh	CHP Run Time (mins)
60 to 85	89.95	200

Table 1: Energy stored by PCM during charging from 60C to 85C.

Comparing the energy storage densities over the operating range of the building heating system, the PCM-TES holds 6.56 times more heat energy.

7. CHP electrical operation during charging

The significance of charging times and storage density has a direct influence on the electrical operation of the CHP. When testing the CHP power output, both storage units were charged from ambient temperature to full operating temperature. When the SH-TES was fully charged, the unit was discharged directly into the building to allow the CHP recharge the tank a number of times as shown in Figure 7. Significantly, the SH-TES was charged three times in the same period it took to charge the PCM-TES from ambient. However, this represents three starts for the CHP whereas the CHP runs continuously when charging the PCM-TES.

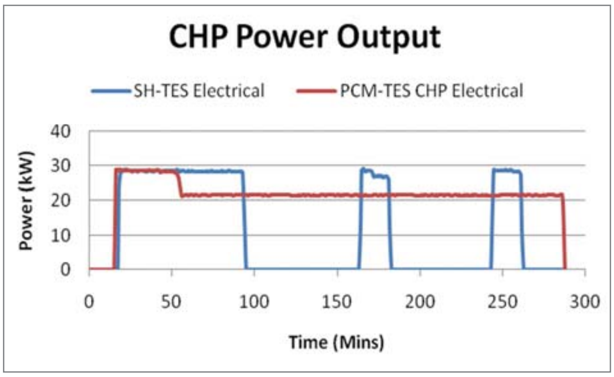

Figure 7: CHP electrical output when charging the PCM-TES and SH-TES from fully cold.

The electrical output totals are shown in Table 2. The CHP runs continuously as the PCM-TES charges. Compare this to the SH-TES which charges from cold three times faster than the PCM-TES but as a consequence the electrical outputs are far lower over the first 150 minutes. The SH-TES is discharged twice in order to compare the total possible CHP operation over a single charge time of the PCM-TES.

Average PCM-TES charging Electrical Output kWe	103
Average SH-TES charging Electrical Output kWe	61

Table 2: The average electrical output during charging of the thermal storage units.

8. Discharging performance comparison of the PCM-TES

The results presented in this section show the SH-TES and PCM-TES discharging characteristics when feeding the building heating manifold early morning prior to the CHP starting at 7am. Normally when the CHP starts, the back-up gas boilers activate as there is a large demand due to all the cold liquid in radiators and piping in the building overnight. Figure 8 shows the operation of the gas boilers.

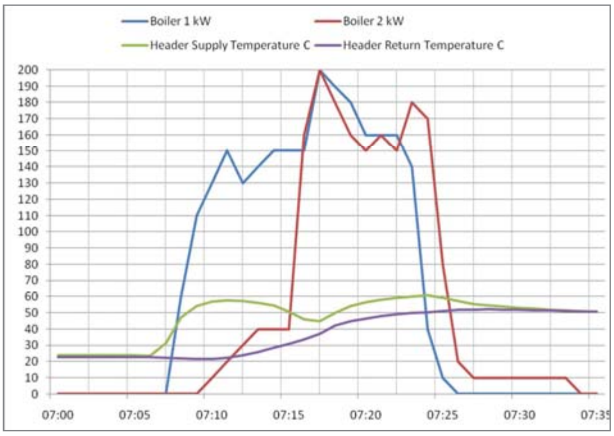

Figure 8: Gas boiler heat curves when assisting the CHP early in the morning.

The total additional energy used by the boilers which is derived from gas is calculated from Figure 8 and shown in Table 3.

Boiler 1 kWh	Boiler 2 kWh	Total kWh
37.93519	29.70833	67.64352

Table 3: Gas energy consumed by the backup gas boilers without the PCM-TES fitted.

The minimum requirement for any thermal storage device installed in the current building must be above 67.64kWh if the boiler gas costs are to be eliminated. The current 2000 litre SH-TES only stores 13.4 kWh. If the energy was stored in a water tank for the operating differential temperatures of the heating system, the 10000-litre tank would be required. The discharge curve for the 2000-litre SH-TES is shown in Figure 9. The discharge only takes eight minutes due to a combination of the low level of energy stored and the rate at which the stored energy can be released.

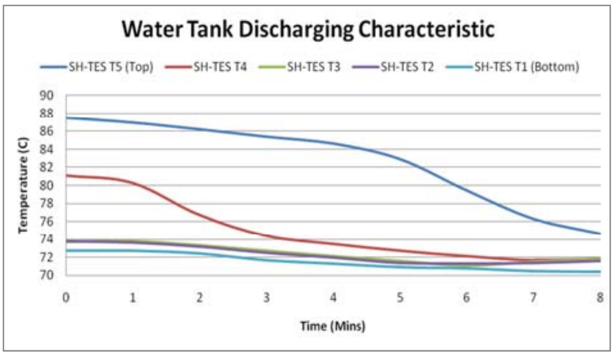

Figure 9: Discharge characteristic for the SH-TES.

The PCM-TES discharge is shown in Figure 10. The discharge in this case takes 50 minutes to reach 70°C from a fully charged state. The time to discharge is a combination of the 6.5 times higher energy density and the lower rate of release of energy from the PCM material.

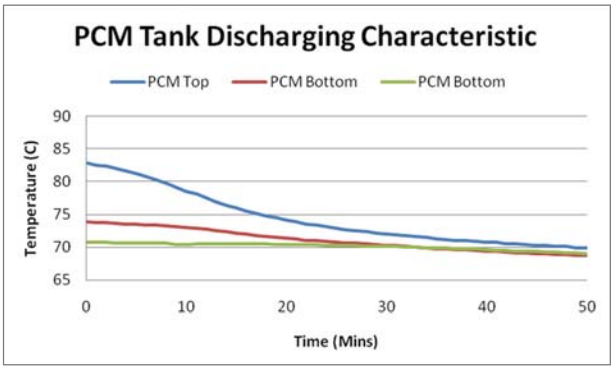

Figure 10: Discharge characteristic for the PCM-TES.

This longer discharge time of the PCM-TES can be compensated for by programming the SCADA/BMS system to discharge the PCM-TES 50 minutes before the CHP starts at 7am. The only reason the CHP starts at 7am is due to the economics of the feed-in tariff periods. The boilers never kicked in when the PCM-TES discharges early morning. The PCM-TES and CHP working together never cause the header return temperatures to drop below the activation set-point temperatures of Boiler 1 or Boiler 2 after 7am. Using the data in Table 3, a saving of 67.64 kWh of gas per heating day is achieved by allowing the PCM-TES to discharge and eliminate the need to use the backup boilers.

9. Discussion

The charging and discharging results show that the PCM-TES holds 6.5 times the heat energy of a SH-TES water tank of identical volume when connected to this CHP operating on a 90/70°C heating system. The advantages of the PCM-TES are that it allows the CHP to run longer when there is no heat demand in the building. This normally coincides with the peak tariff period in the evening which is exactly when commercial building workers leave to go home at the end of their working day. The heat energy is stored overnight and used to pre-heat the building heating system in preparation for when the CHP operates early the following day. This results in the building being at the correct temperature when the workers enter the building at the start of their working day.

Referring back to the economic advantages of installing a PCM-TES, there are three findings made using data generated for the demonstrator PCM-TES.

The first relates to the need for two back-up gas fired boilers. This could be reduced to one single boiler, used primarily when the CHP is being serviced. This represents a capital expenditure saving, a gas saving and an annual maintenance saving.

The second relates to the plant floor space being saved by having one PCM-TES. Five to six water tanks would be required in the demonstrator site to hold the energy of the PCM-TES. Indeed, the

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space saved by having only one backup boiler increases this figure further.

The third relates to the overall electrical performance during peak tariff periods. The PCM-TES allows the generator to run continuously during evening peak tariff windows, maximising the revenues generated for power export, especially as the building occupancy is normally low at the end of the working day.

10. Conclusion

This paper presents real building performance data for a novel design PCM-TES. The PCM-TES has been installed in a commercial building and its operation is compared to a SH-TES of the same size. Results show the PCM-TES holds 6.5 times more heat, allows the CHP to run longer at peak tariffs and has the capacity to eliminate one of the backup gas boilers, saving on CapEx and gas energy consumption when compared to the SH-TES.

It is concluded that the demonstration of a 6.5:1 energy density ratio for the same plant room space represents a viable proposition for heating system design engineers.

The current technology is now being designed to reduce the embodied energies by considering alternative materials to the stainless steel and using bio-degradable PCM materials which will influence the life-cycle costs and sustainability of this novel thermal energy storage technology.

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