CLOSING THE GAP BETWEEN DESIGN AND REALITY OF BUILDING ENERGY PERFORMANCE

Case study on an educational building

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Executive summary

Phase Change Materials (PCM)-based thermal energy storage systems can significantly improve the energy efficiency of the Heating Ventilation and Air-conditioning (HVAC) system of buildings. This report presents the findings of a case study that has been carried out to understand the factors that may contribute to the gap between designed and actual energy savings performance of a PCM integrated HVAC system in a building. The selected case study building is an 11-story educational building located approximately 8km from the Melbourne Central Business District, Australia. The installed PCM system in this building was designed to reduce the peak cooling load of the HVAC system during the daytime. The results showed that the PCM system does not reduce peak cooling load during summer periods when it is needed the most. Although the system reduces cooling load during the winter, the magnitude is far lower than expected. The factors that have contributed to the performance gap are poor communication between designer and facilities manager regarding PCM system operating principles, poor quality of phase change materials, lack of facility manger's knowledge on PCM technology, lack of accountability and incomplete commissioning.

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1 Case study context

The selected case study is an 11-story educational building located approximately 8km from the Melbourne Central Business District, Australia. The building has achieved a 5-star GreenStar sustainability rating from the Green Building Council of Australia. The predicted electricity consumption for this building is around 641 MWh/year. However, from July 2017 to June 2018, the building consumed 1700 MWh electricity which represents a significant energy performance gap. The actual energy consumption is about 2.6 times that of the predicted energy consumption. There may be a number of factors that have contributed to this large discrepancy between actual and predicted consumptions. In this study, the research scope is limited to the performance of the Phase Change Materials (PCM)-based thermal energy storage system that has been integrated with the HVAC system of this building to minimise the peak HVAC cooling load during the daytime.

2 Aims and objectives

This study aims to understand the factors that contributed to the gap between designed and actual energy saving performance of the PCM system. The specific objectives are:

1. Understand the working principle of the PCM system through document analysis and collecting the historical operational data from the building management system.
2. Calculate the energy saving performance of the PCM system through analysing collected data.
3. Investigate the factors affecting the gap between the designed and actual energy saving performance of the PCM system.

3 Brief description of phase change materials

Phase change materials (PCMs) absorb or release the energy equivalent of their latent heat when the temperature of the material undergoes or overpasses the phase change temperature [2]. Figure 1 shows a typical temperature vs stored heat curve for both the sensible and latent heat storage system. In the case of the sensible heat storage system, the temperature of the building material increases continuously with stored thermal energy. For the latent heat storage system, energy is stored as sensible heat until the temperature reaches the phase change temperature. At this point, phase transition occurs from solid to liquid or liquid to gas and energy is stored as latent heat at nearly constant temperature. When the phase transition is completed, energy is stored as sensible heat again. The latent heat storage system is highly attractive due to its higher heat storage capacity per unit volume compared to the sensible heat storage system [3]. When the ambient temperature drops again, the PCM returns to its previous state by giving off the absorbed heat. This cycle stabilises the interior temperature and cuts off cooling and heating loads. Incorporation of latent heat thermal energy storage (LHTES) systems with PCMs in buildings has recently received significant attention as a potential technology to enhance building energy efficiency.

Previous studies showed that PCMs could significantly improve the efficiency of the HVAC system with a substantial reduction in energy use. PCMs can be integrated into traditional HVAC systems such as absorption chillers [4, 5], evaporative and radiative heating-cooling systems [6-9], air-conditioning systems [10-12], and domestic ground heat pumps [13, 14]. Helm et al. [4] studied the performance of an absorption cooling system containing a salt hydrate PCM with the melting temperature of 27-29°C. The results of pilot scale experiments showed that the PCM absorbed up to 50% of daily rejected heat load when outdoor temperatures were above 30°C and ensured a 32°C constant cooling water supply to the chiller. Zhang and Niu [6] designed and numerically evaluated the performance of a hybrid cooling system consisting of a 18°C microencapsulated PCM (MPCM) slurry storage tank and nocturnal sky radiator. During night time, the radiator stores the 'coolth' of ambient air in the storage tank. During daytime, the cold storage of MPCM slurry contributes to the building cooling load demands through chilled beams. The proposed system saved the energy use by up to 77% and 62% in low rise buildings in Lanzhou and Urumqi, China, respectively. In another study[7], the integration of PCM in the radiant

floor system was found to reduce peak floor temperature by 3.5°C and decrease the cooling water usage by 25% in the summer season.

Several studies incorporated a PCM heat-exchanger in the air-duct to pre-condition the air to improving HVAC efficiency [12, 15]. However, it is worth noting here that these studies were either conducted on pilot scale experiments or numerical analysis of full-scale buildings assuming proper installation and smooth operation of the PCM system as intended, with no disturbances from surrounding environments and activities. In reality, there are a number of factors from the design, construction and operational stages that may lead to underperformance [16].

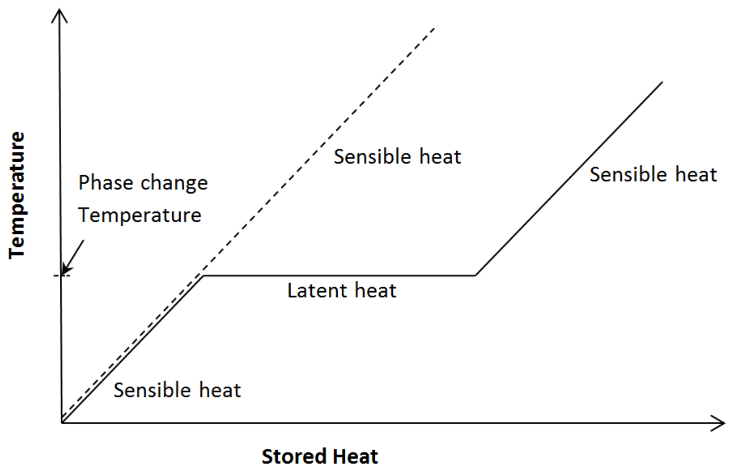

Figure 1 Typical temperature vs stored heat curve for a thermal energy storage system

4 Description of the PCM system installed in the case study building

In the selected case study building, the required heating and cooling load are supplied via active and passive chilled beams. A secondary chilled water (SCHW) system serves those active and passive chilled beams throughout the building via a secondary chilled water loop as shown in Figure 2. The required chilled water for the SCHW loop is generated from the primary chilled water (CHW) system water loop via a plate heat exchanger (HX-11-03). A water-cooled electric chiller is used to generate chilled water in the CHW system water loop. In addition to the chilled water being generated directly from the CHW system, the SCHW loop is also supplemented by the phase change material tank (also shown in Figure 2) to reduce the cooling demand on the chillers. Cooling energy stored in the PCM tank is transferred to the SCHW system via PCM heat exchangers (HX-11-02). At night, the 'coolth' of the ambient air temperature is stored in the PCM tank using the adiabatic cooler in the condenser water system (CCW).

The PCM tank is located in the plant room (11th level) of the building. The exterior view of the tank is shown in Figure 3. The internal dimension of the PCM tank is 5000 mm long X 4000 mm wide X 2000 mm high. All sides, roof, and base of the tank are insulated to prevent unwanted heat transfer with the surrounding environment. Inside the PCM tank, 5120 FlatICE PCM panels are stacked in 40 layers where each layer has 8 blocks along the length and 16 blocks along the width of the tank as shown in Figure 4. Each PCM panel has a dimension of 500 X 250 X 45 mm and contains an external guided circle (see Figure 5) which ensures a small gap between the containers when stacked inside the tank. In order to store or extract cooling energy from the PCM panel, water is used as a heat transfer fluid (HTF). The gaps between the containers allow water to flow over the container and maximises the heat transfer between the PCM panel and water. Two stainless steel diffuser plates, spaced at 200 mm from the walls, were employed to confine the PCM panels on both sides. The plates contain a number of 8mm holes along the gap between containers as shown in Figure 4. This arrangement ensures even water flow through the gaps between containers and maximises the extraction of cold storage from the PCM tank.

PCM panels are made of high-density polyethylene (HDPE) container and contain 3 kg inorganic hydrated salt. The manufacturer specifications of the PCM are given in Table 1.

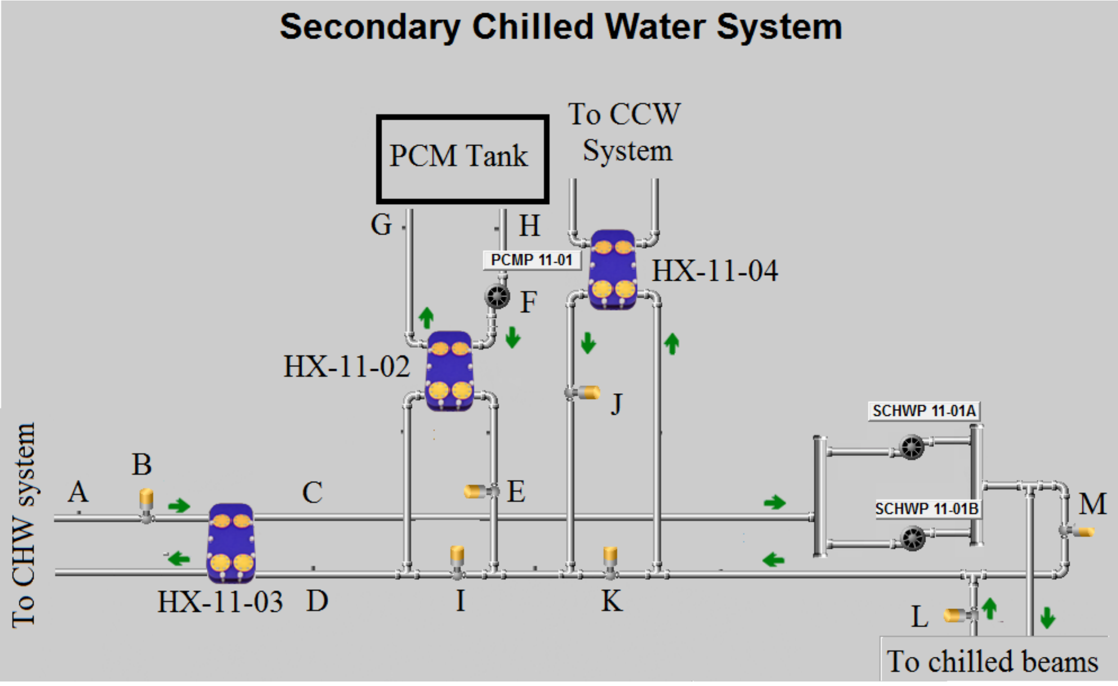

Figure 2 Secondary chilled water system integrated with PCM tank

Figure 3 Phase change materials tank in AMDC building

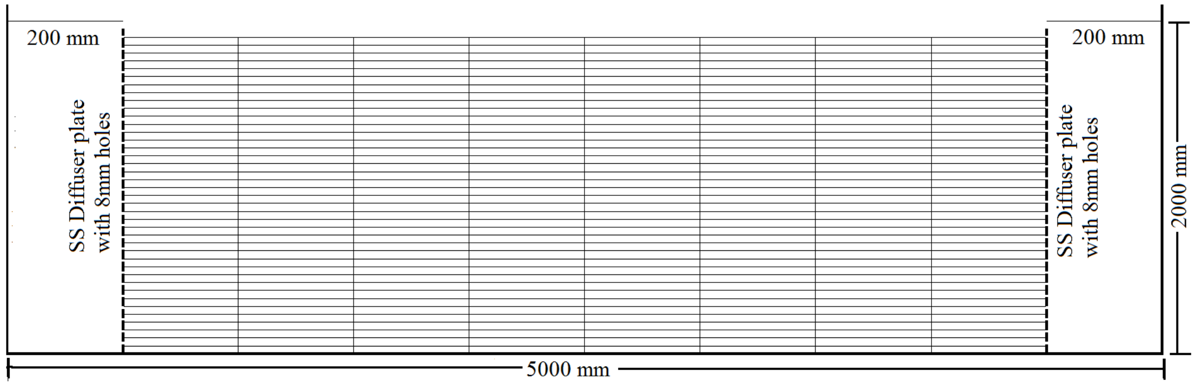

Figure 4 Schematics of PCM block arrangement in PCM tank

Figure 5 FlatICE PCM blocks inside the PCM tank

Table 1 Properties of PCM used in the FlatICE block

Properties	**Value**
Phase change temperature	15°C
Density	1510 kg/m^3
Latent heat capacity	160 kJ/kg
Specific heat capacity	1900 kJ/kg.K
Thermal conductivity	0.43 W/m.K

4.1 Operation of Secondary Chilled Water (SCHW) system

The SCHW system operates in two stages to meet the cooling demand. Stage 1 involves the extraction of cooling energy from the PCM tank via the PCM heat exchanger (HX-11-02) and the operation chilled water heat exchanger as a supplement. Stage 2 involves the operation of the chilled water heat exchanger to supply chilled water generated by the chiller to the chilled beams.

4.2 PCM discharging in Stage 1

Whenever there is a cooling call, the system starts with Stage 1. When Stage 1 is active, and energy stored in the PCM tank is sufficient to provide cooling, then the bypass valve 'I' (see Figure 2) is closed, control valve 'E' is open and phase change pump 'F' is run at a predetermined speed. Once the stored cooling energy of the PCM is exhausted or is insufficient to generate the required chilled water for the SCHW loop, the system moves to Stage 2.

4.3 PCM charging

Figure 6 shows the conditions of the PCM tank charging. The PCM tank charging mode is activated when the following conditions are true for 1 hour:

1. There is no cooling call from the building
2. Outdoor ambient air temperature is less than 11°C

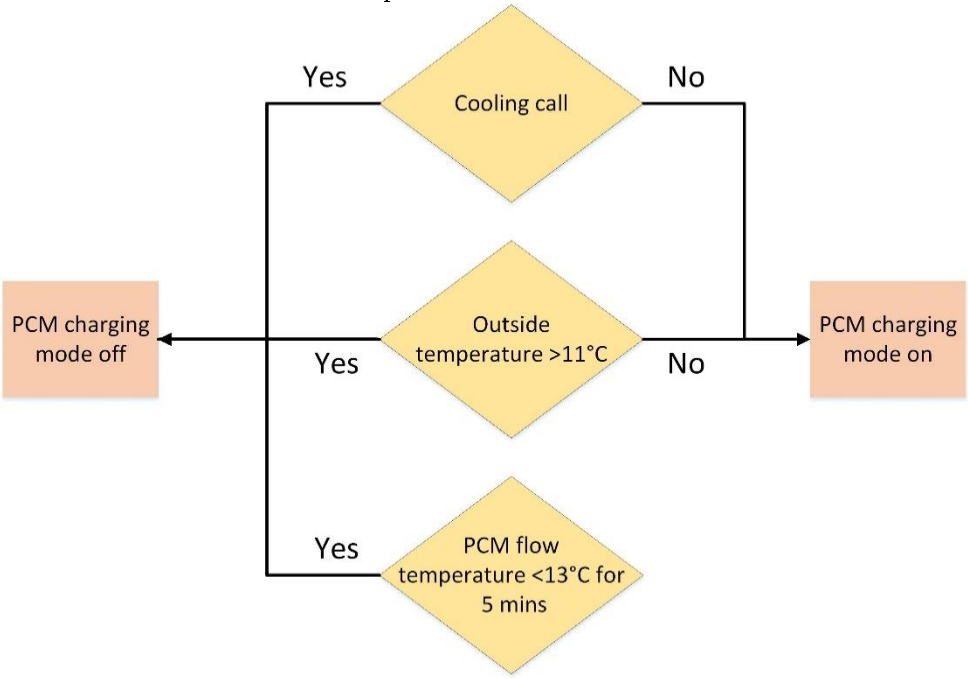

Figure 6 Conditions for PCM tank charging mode on/off

Once the PCM charging mode is activated, the valves in the SCHW system (in Figure 2) are commanded to the positions shown in Table 2. The Table also shows the valve positions during the PCM discharging mode. Once the required valve combination for PCM charging is true for 60 seconds, the duty secondary chilled water pump (either SCHWP 11-01A or SCHWP 11-01B), phase change material pump (F), and condenser water pump in the CCW system are commanded on at a fixed speed. In PCM charging mode, the adiabatic cooler ACC- 11-03 (shown in Figure 7) provides cooling water for the PCM tank utilising the cold ambient temperature and via the heat exchangers HX-11-04 and HX-11-02.

Table 2 Valve positions in PCM charging and cooling mode

Valve	**PCM charging**	**PCM discharging**
SCHW bypass valve (M)	On	Off
SCHW return valve (L)	Off	On
HX-11-04 bypass valve (K)	Off	On
HX-11-04 control valve (J)	On	Off
HX-11-02 bypass valve (I)	Off	Off
HX-11-02 control valve (E)	On	On

Figure 7 Adiabatic cooler of the CCW system

5 Data collection and analysis

The operational data of the PCM system from May 2016 to June 2018 were downloaded from the Building Management System (BMS) and analysed to calculate the performance of the system. Table 3 illustrates the monitored parameters along with their operation mode and measurement accuracy. The parameters were recorded at a frequency of 5 minutes in the BMS system. The notations given in brackets refer to the location in the SCHW system shown in Figure 2. The specifications of the pumps were recorded from the HVAC Commissioning report of the building and are presented in Table 4.

The performance monitoring of the active PCM system resulted in a large amount of data collection that provided insights into the PCM performance in supplying the cooling energy. In order to systematically assess this massive data collection, the following indicators were used in this study.

Table 3 Monitored parameters of the active PCM system

Parameter	Unit/operation mode	Accuracy
CHW Flow Temperature (A)	℃	±0.1℃
HX 11-03 Control Valve (B)	On/off	-
HX-11-03 SCHW Flow Temperature (C, T_C)	℃	±0.1℃
HX-11-03 SCHW Return Temperature (D, T_D)	℃	±0.1℃
HX-11-02 Control Valve (E)	On/off	-
PCMP-11-01 Run Status (F)	On/off	-
PCM Flow Temperature (G, T_G)	℃	±0.1℃
PCM Return Temperature (H, T_H)	℃	±0.1℃
HX-11-02 Bypass Valve (I)	On/off	-
HX-11-04 Control Valve (J)	On/off	-
HX-11-04 Bypass Valve (K)	On/off	-
SCHW PCM Charging Call	On/off	-
CHW/SCHW Cooling Call	On/off	-
SCHW Stage 1 Cooling Status	On/off	-

Table 4 Specification of pumps used in the PCM charging and cooling process

	Phase change material pump (PCMP-11-01)	Condenser water pump (CCWP-11-04)	Secondary Chilled water pump (SCHWP-11-01A)	Secondary Chilled water pump (SCHWP-11-01B)
Power (kW)	15	11	18.5	18.5
Flow rate (L/s)	28	21.5	26.1	26.1
Efficiency (%)	93	92	94	94
Speed (RPS)	1450	1450	1460	1460
VSD (HZ)	35.4 (71%)	41 (82%)	43 (86%)	42.9 (86%)

5.1 Cooling energy supplied by the PCM tank to the SCHW system

When there is sufficient cold storage in the PCM tank, and there is a cooling call to the system (conditions mentioned in Section 4.2 are met), the cooling energy supplied by the PCM tank to the SCHW system is calculated as follows:

$$Q_{cpcm} = \dot{m}C_p(T_G - T_H) \times t \qquad (1)$$

Where Q_{cpcm} is the cooling energy supplied by PCM (KJ), $\dot{m}$ is the mass flow rate of water through the PCM tank (kg/s), C_p is the specific heat capacity of water (KJ/kg.K), T_G and T_H are the water inlet (point G in Figure 2) and outlet temperature (point H in Figure 2) from the PCM tank respectively and t is the duration.

5.2 Cooling energy supplied by the CHW system to the SCHW

During Stage 1 and Stage 2 cooling, the cooling energy supplied by the CHW system to the SCHW system is calculated using equation (2):

$$Q_{CHW} = \dot{m}C_p(T_D - T_C) \times t \qquad (2)$$

Where Q_{CHW} is the cooling energy supplied by the CHW system (KJ), $\dot{m}$ is the mass flow rate of water through the heat exchanger HX-11-03 (kg/s), C_p is the specific heat capacity of water (KJ/kg.K), T_C and T_D are the water flow (point C in Figure 2) and return temperature (point D in Figure 2) from HX-11-03, and t is the duration.

The percentage of cooling energy supplied by the PCM tank (E_{PCM}) and CHW system compared to total cooling energy consumed by the chilled beam system is calculated via:

$$E_{PCM} = \frac{Q_{cpcm}}{Q_{cpcm}+Q_{CHW}} \times 100 \qquad (3)$$

$$E_{CHW} = \frac{Q_{CHW}}{Q_{cpcm}+Q_{CHW}} \times 100 \qquad (4)$$

5.3 Cooling energy stored in the PCM tank

When the PCM charging conditions mentioned in section 4.3 are met, cooling energy stored in the PCM tank is calculated using equation (5):

$$Q_{spcm} = \dot{m}C_p(T_H - T_G) \times t \quad (5)$$

Where Q_{spcm} is the cooling energy stored in the PCM tank (KJ), $\dot{m}$ is the mass flow rate of water through the PCM tank (kg/s), C_p is the specific heat capacity of water (KJ/kg.K), T_G and T_H are the water inlet (point G in Figure 2) and outlet temperature (point 'H' in Figure 2) from the PCM tank respectively and t is the duration.

5.4 PCM tank cooling capacity

As mentioned in Section 4, the PCM tank contains 5120 FlatICE PCM blocks. Each block contains 5.74 kg PCM. Using the manufacturers' specifications of PCM (Table 1), the total capacity of the PCM tank can be calculated as follows:

Total PCM tank cooling load capacity = Number of PCM blocks x weight of each block x latent heat capacity of each block
= 5120 X 5.74 kg X 160 KJ/kg
= 4702208 KJ

Hence, if the PCM tank is fully charged, it can provide 4702.2 MJ or 1307 kWh cooling load shifting capability to this building.

6 Results

Figure 8 presents the cooling energy stored and delivered by the PCM tank to generate chilled water in the SCHW loop. The cooling energy stored was calculated using equation (1). The graph shows that the PCM tank provided cooling energy during late autumn (May), winter (June – August) and early spring (September – October). The tank was inactive during the summer period (December – March). This was because, during summer, the PCM tank was not charged at night to deliver cooling energy during the daytime as shown in Figure 8. During the summer months of 2016-2017 and 2017-2018, the monthly mean minimum temperatures were between 14.6°C and 17.3°C as shown in Figure 8. The PCM tank starts charging only when the outdoor temperature drops below 11°C. In 2016-2017 summer, only 9 nights out of 4 months experienced minimum temperatures below 11°C. The 2017-2018 summer nights were even hotter where only 4 nights experienced minimum temperatures below 11°C. Figure 8 shows that mean minimum night temperatures during May to October were well below 11°C (except May-16 and Oct-17) which provided favourable conditions for the PCM tank to be charged at night. During this period, the PCM tank supplemented the cooling energy requirement (Figure 8) in the building by utilising energy stored at night. Although in May 2016, the mean minimum temperature was 11.4°C, this month experienced 11 nights with minimum temperatures much lower than 11°C. The mean minimum temperature of the last 11 nights of May 2016 was only 8.5°C which provided favourable conditions for the operation of the PCM tank. The same explanation applies to the operation of the PCM tank in October 2017.

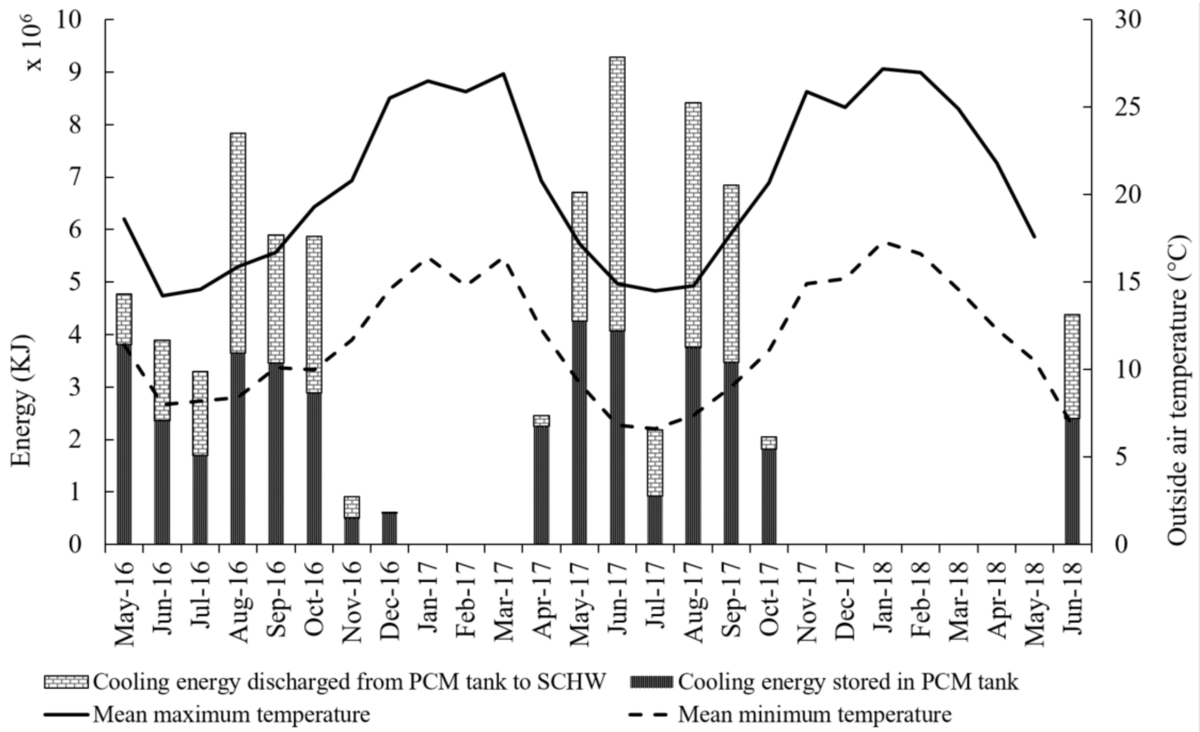

Figure 8 Monthly cooling energy stored and discharged from the PCM tank along with mean maximum and minimum outdoor temperatures

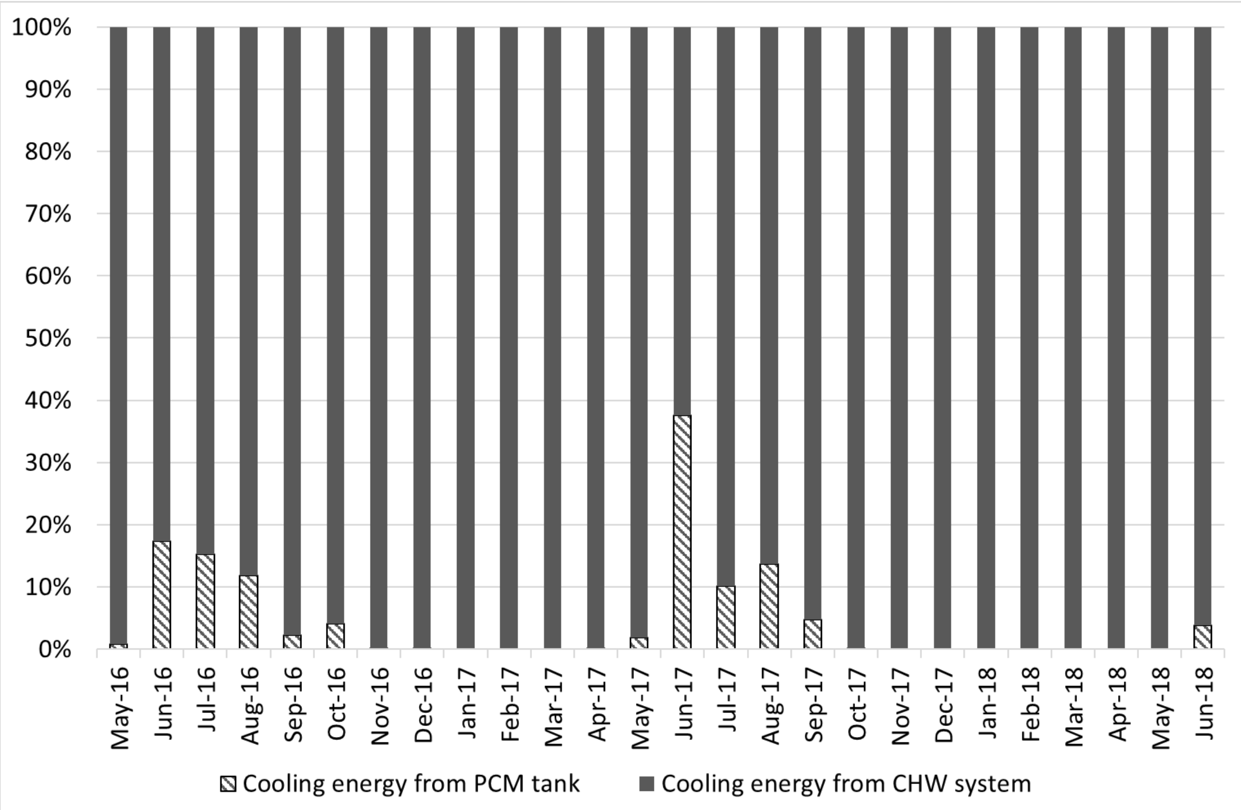

Figure 9 Monthly cooling energy supplied by the PCM tank and CHW system as a percentage of the total cooling energy consumed

Figure 9 shows the cooling energy supplied by the PCM tank and CHW system as a percentage of total cooling energy delivered to the SCHW system to meet the building cooling demand, calculated using equations (3) and (4). As expected, the PCM tank contributed to meet cooling demand only during the winter months (June to August) compared to others. Between 12-37% of the total cooling load was delivered by the PCM tank in those months. In addition, the PCM tank contributed around 2-5% of the total cooling load during May, September and October. During the rest of the months, the PCM system remained inactive.

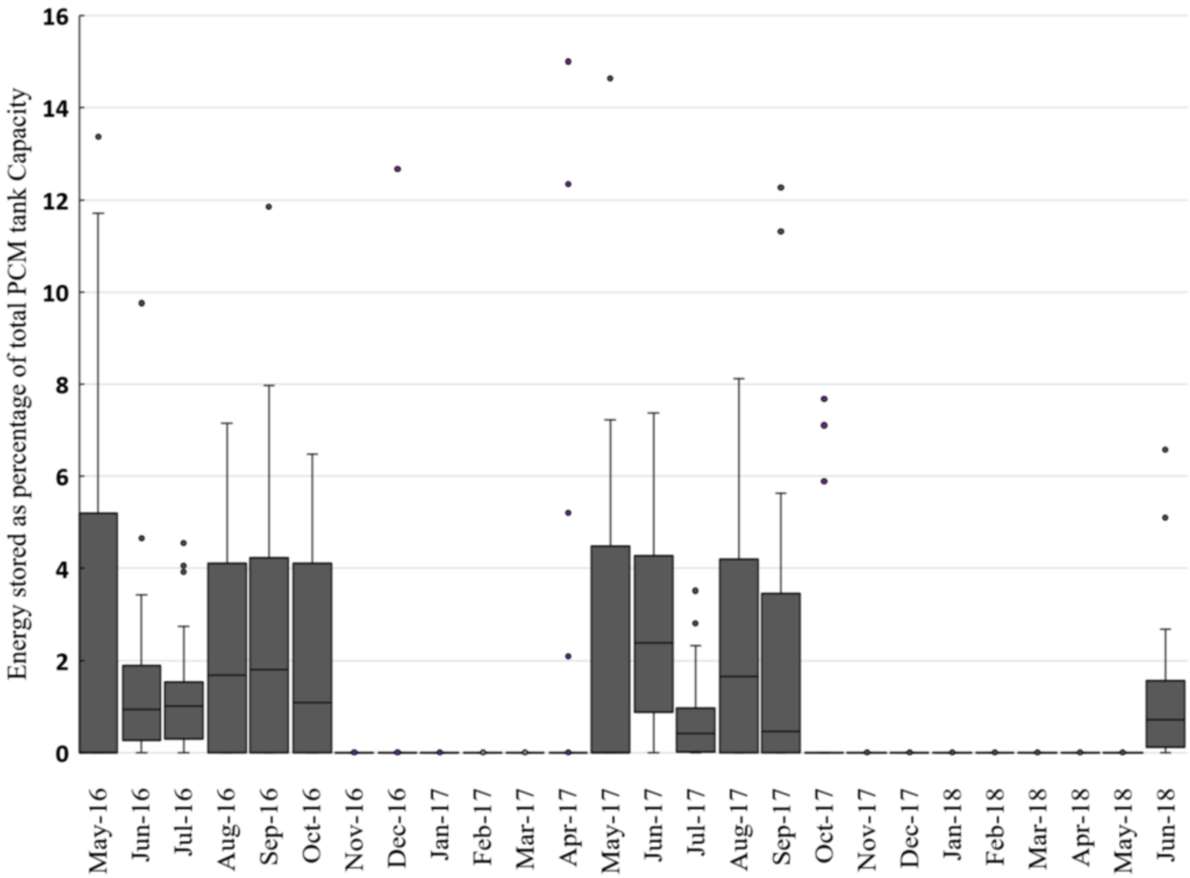

Figure 10 Cooling energy stored in the PCM tank as a percentage of total PCM tank capacity

Figure 10 shows the monthly energy stored in the PCM tank as a percentage of total PCM capacity. It can be seen that this ratio is higher during the winter than the other three seasons. This can be attributed to the availability of sufficient cold storage from ambient air at night during this period, as explained above. The box plot shows the median of the percentage of energy stored, as well as the values within +/- 25% of the median. The whisker plot shows how large is the spread of the data (percentage of energy stored). For example, in June 2017, the median energy storage was 2.4% of total PCM tank capacity which means that on 50% of the days in June 2017, the energy stored in the PCM tank was 2.4% of total capacity or lower. The box plot of June 2017 shows that on 50% of the days the energy stored in the PCM tank was between 1 to 4.2% of total PCM tank capacity. For 25% of the days in June 2017, the energy storage was between 4.2 and 7.2%. For the remaining 25% of the days, energy storage was less than 1%. Interestingly, in May 2016 and May 2017, the median for energy storage was zero because for more than 50% of the days in those two months the energy stored in the PCM tank was zero because of unfavourable weather conditions. Figure 10 also shows a number of outliers which points out that on some rare occasions the percentage of energy storage was much higher than the usual ranges (defined by box and whisker) due to favourable weather conditions on those particular days. However, these are not regular events and should not be used as an indicator of PCM tank performance. More importantly,

the magnitude did not exceed 15% during the entire monitoring period even including the outliers. This indicates that even at maximum utilisation of the PCM tank, it was only using 15% of its available capacity to supply cooling energy to the SCHW loop. One or more of the following conditions may have contributed to this underperformance:

1) An oversized PCM tank
2) The operation mode of the SCHW system is ineffective to efficiently store and retrieve cooling energy from the PCM tank
3) The PCM may not work as specified by the manufacturer

With all three cases, the material specification of the PCM can be considered as a critical parameter to the poor performance of the PCM tank system. This is because the performance assessment of the PCM tank (i.e. diurnal energy retrieval to storage ratio) was conducted using the latent heat capacity of the PCM provided by the manufacturer. In reality, those properties may be different from the supplied specifications by the manufacturer. To determine actual thermal properties of the PCM, a differential scanning calorimetry (DSC) was used. The melting heat transfer behaviour of the PCM and its latent heat capacity were tested. The DSC thermograph of the salt hydrate along with the thermo-physical properties in terms of its onset and peak temperatures as well as the latent heat capacity are presented in Figure 11. This shows that the salt hydrate used in this building has a very high degree of supercooling during the solidification process. Therefore, the solidification process of the PCM required longer periods of cold storage supply and hence, making it unable to supply sufficient cold storage to operate the SCHW system. Furthermore, the measured latent heat capacity of the PCM (53 J/g) was much lower than the manufacturer specified latent heat capacity (160 J/g). These differences lead to a significant variation in the actual performance of the PCM tank to the expected design performance.

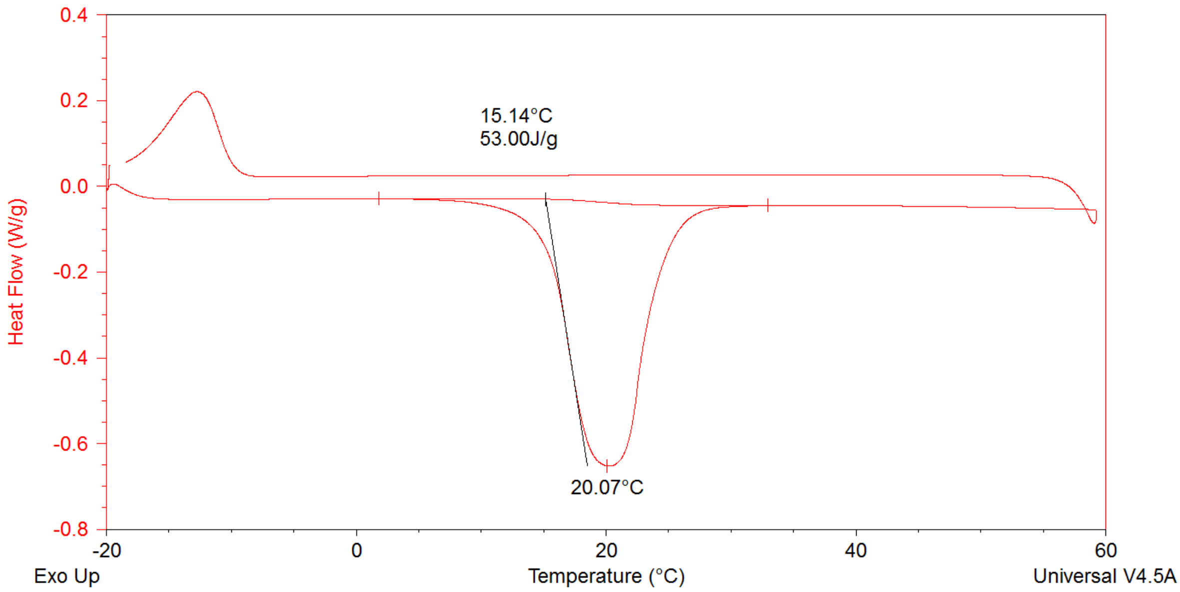

Figure 11 Differential scanning calorimetry measurement of the PCM used in the active PCM system

7 Factors affecting the PCM system performance gap

The monitoring of the thermal performance of an active latent heat storage technology in a multi-story building revealed several limitations during the implementation of the theoretical design in actual buildings. The actual operation of the PCM system revealed a meagre reduction in cooling energy demands. The reason for such low performance of the PCM tank could be attributed to the large degree of supercooling of the PCM (as obtained from the DSC results), low latent heat capacity and inefficient operation of the active PCM system.

A thorough review of the Building Users' Guide revealed that the PCM tank was designed to be charged at night using both ambient air and an electric chiller. The electric chiller should be used when the outdoor ambient air is insufficient to solidify the PCM. In this way, the chillers can operate more efficiently due to cooler ambient temperatures and can take advantage of the off-peak electricity tariff which is 25% lower than the peak in this case study. However, in reality, this active PCM system was only operated in a free cooling mode (using the ambient air only to solidify the PCM) which caused the PCM tank to be inactive during the summer period. This happened because the requirement of running the chiller at night to charge the PCM tank was not mentioned in the Building Management System (BMS) operating and maintenance manual and the current operation mode was programmed to charge the PCM using cold night ambient air only. Communication with the operation manager revealed that they were not aware of this requirement of running chillers to charge the PCM tank at night. They were running the building according to the instructions provided to them by the consultants, and they had not gone through the Building Users' Guide. Moreover, from the communication with the building operation manager and service engineer, it was understood that there is a lack of understanding amongst the operation and maintenance staff regarding the operation and purpose of PCM technology. As a result, the PCM tank was not running efficiently to minimise the peak cooling load of the building.

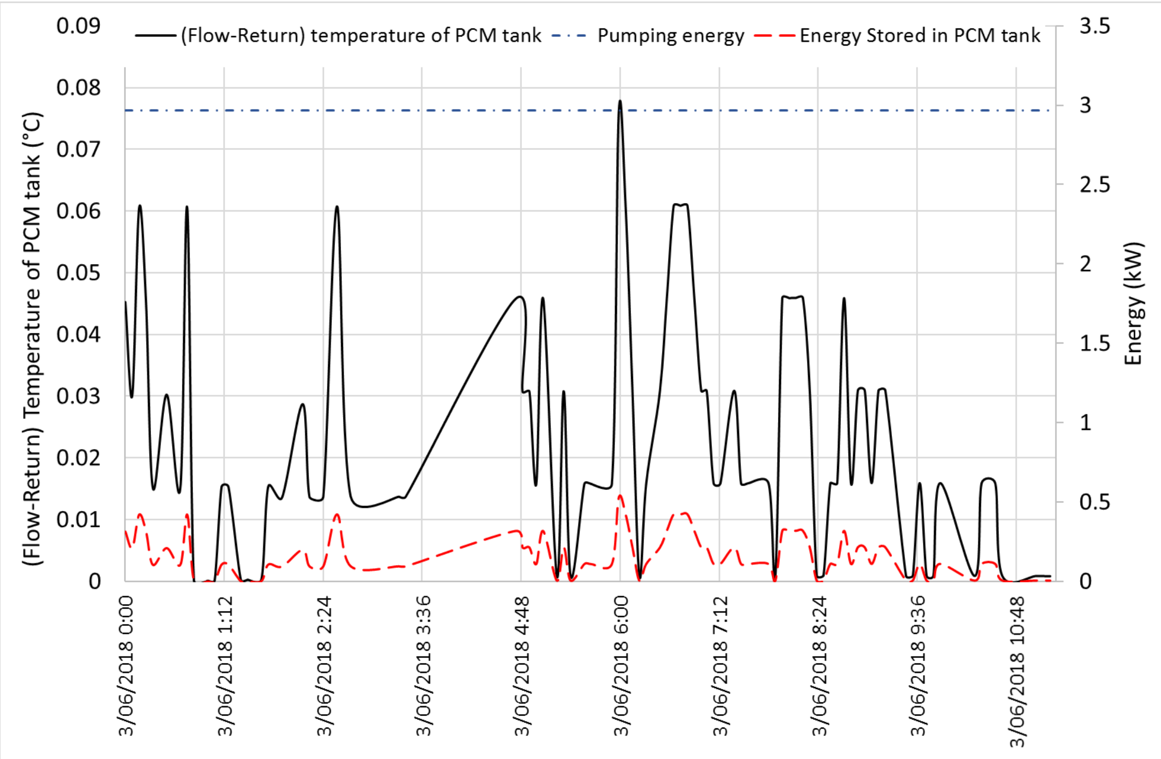

Figure 12 Energy stored in PCM tank and associated pumping energy on 3rd June 2018

Figure 12 shows the temperature difference between the flow and return points in the PCM tank along with the energy stored in the PCM tank on 3rd June 2018. The figure also shows the energy consumed by pumps to store that energy. The power consumed by the pumps was calculated with the aid of the pump specification (Table 4) and hours of operation. As can be seen from Figure 12, the average difference between PCM flow and return temperature was only 0.023°C with a maximum difference of 0.075°C. The energy stored in the PCM tank was consistently lower than the energy consumed by the pump to store that energy. The total energy stored in the PCM tank on this occasion was determined as 13.51 kW. In order to attain this energy storage, three pumps were running for 11 hours and consumed 419.65 kW. This indicates that the energy storage of the PCM is insignificant compared to the energy required to attain this storage. Instead of saving energy, the PCM system is consuming more energy

while charging and discharging which is negatively influencing the energy efficiency of this building. Hence, the PCM charging operation should be revised to include a minimum temperature differential as an additional condition in order to turn on the charging mode, as shown in Figure 6.

From November 2017 to May 2018, the PCM system was found to be inactive, since there was no cooling or charging of the PCM tank evident from Figure 8. The PCM tank was completely inactive during April and May 2018 which was not expected when comparing the operation of the PCM system with previous years. Further analysis of the collected data revealed that in those months there was always a cooling call from the building. As a result, the PCM tank was never charged (condition in Figure 6) in that period and hence, the PCM tank did not deliver any cooling energy to the SCHW loop. A review of the building maintenance log and communications with the building operation manager and service engineer revealed that the occupancy detection sensors were not working in several zones of the building in November 2017. This issue was impacting the operation of the heating and cooling system in those zones as the system only turns on when there is an occupant in the room. To overcome this issue temporarily, the occupancy control of the HVAC system was overridden in the BMS which resulted in a 24/7 cooling call from the building irrespective of occupancy status. As a result, the PCM tank charging mode was off for 7 months until the problems with the occupancy sensors were fixed in June 2018. During this time, the operational staff were unaware of the fact that the PCM operation was affected by this overriding decision, due to their lack of knowledge and understanding of the active PCM system.

Based on the above discussions, the factors that contributed to the energy saving performance gap of the PCM system are presented in Figure 13.

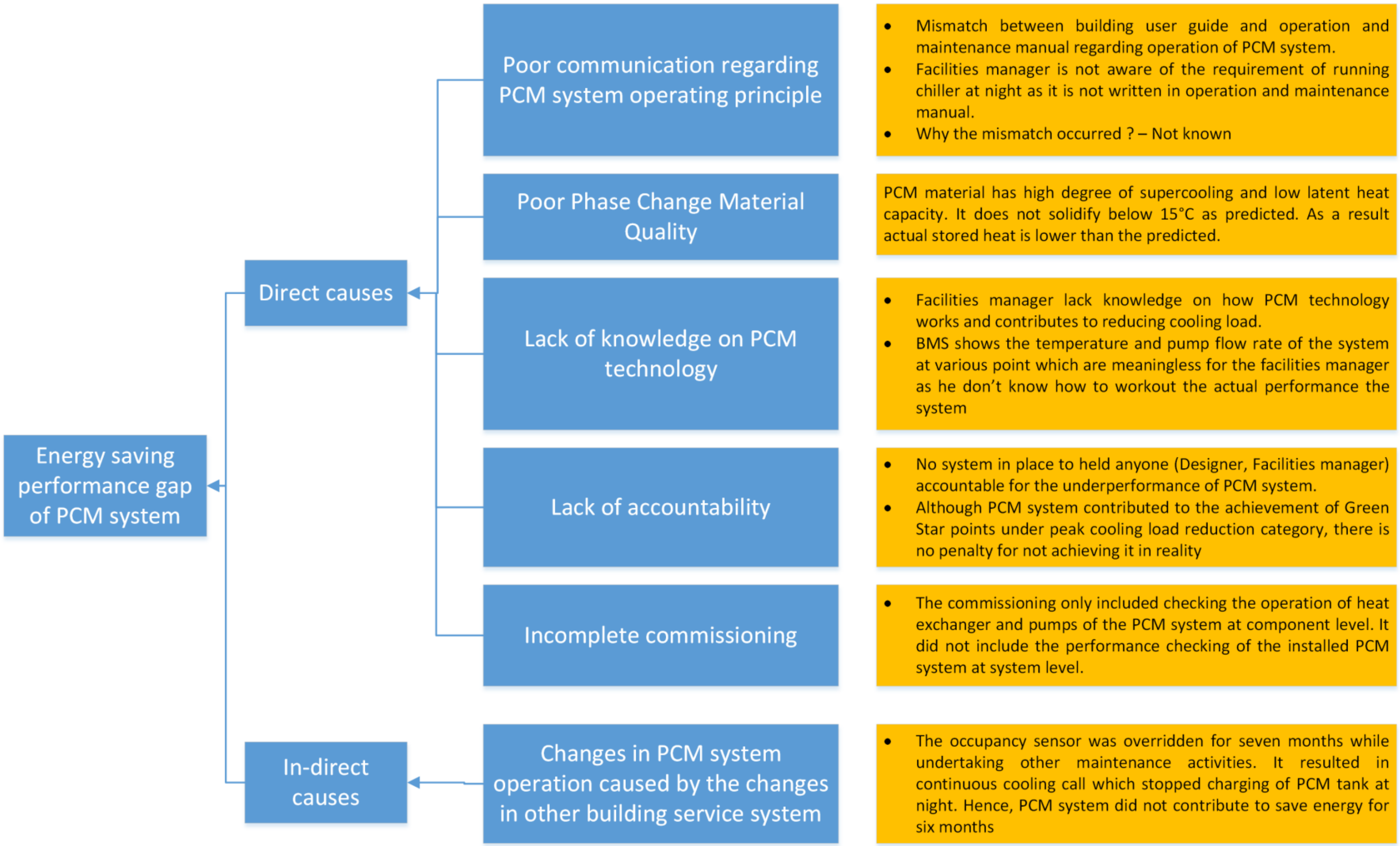

Figure 13 Factors affecting the energy saving performance gap of the phase change materials system.

8 Lessons learned

The following are the critical lessons learned from this case study:

1. The control logic for charging and discharging the PCM tank should be checked at regular intervals to explore the possibilities of improving its efficiency. The PCM tank should not charge when the pumping energy required to charge the PCM tank is significantly higher than the cooling energy stored in PCM tank.

2. The material specification of the PCM should be carefully assessed to eliminate potential negative impacts of the PCM during its operation.

3. The difference between the designed and actual operation of the PCM system will cause the PCM tank to perform poorly. To maximise the efficiency of the PCM tank and to minimise building energy consumption, the designed operation of the PCM system should be communicated clearly with building operational staff.

4. The building design documents should be ensured as consistent with the operation documents. If there are any changes in the maintenance documents, these should be consulted with the designer to see the potential impact of the changes on the performance of the PCM system.

5. The building operations and maintenance staff should be provided with the necessary knowledge and training to understand whether the PCM system is performing as intended.

9 References

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