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Opportunities of Air- and Water-to-PCM Batteries in Buildings

Peter van den Engel[1]*, Bert van Dorp[2] and Koen Hamers[2]

[1]Department of Architecture, Delft University of Technology, The Netherlands

[2]Orange Climate BV, The Netherlands

ABSTRACT

For a transparent meeting centre at the Green Village of TU Delft, the Co Creation Centre, a large air-to-air PCM battery was integrated in an air handling unit. Based on the experiences with this battery, a new battery was applied in an office building, the Office Lab. Both buildings were used as research facilities. The PCM uses of outdoor and indoor temperatures such as a flexible thermal mass with a high thermal capacity, flattening high and low indoor temperature peaks. In case of very warm of very cold outdoor night temperatures the battery can additionally be loaded with a heat pump. In this way the thermal and electrical capacity of the heat pump can be reduced significantly as well. The battery can be an economic and energetic favourable alternative. Additionally, there is a water-to-PCM battery in the crawl space with the same kind of panels. In the heating season heating energy from the heat pump with a higher temperature can be stored, making use of low, zero or negative electricity prices via solar panels or the grid. A thermal battery can reduce grid congestion as well. The performance of the PCM-batteries is evaluated with a CFD-program (Phoenics), a building simulation program (Design Builder), and additional calculations and measurements as far as possible.

***Corresponding author**

Peter van den Engel, Department of Architecture, Delft University of Technology, The Netherlands.

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Introduction

It is possible to use freely available indoor and outdoor energy stored in a PCM battery for both heating and cooling, in summer and as well in winter by choosing the most suitable phase change temperatures. In two buildings at the Delft University of Technology PCM was integrated into air handling units. The air-to-PCM batteries exhibit a phase change of 17-23°C by combining different panels. In particular, for light weight buildings the diurnal swing can be reduced by PCM, making active heating and cooling less necessary. On top of that, by using the PCM battery undesirable heating up of the thermal mass in the cooling season can be reduced. More thermal mass is not always better, think of a tent in summer which is pleasant in evening and night when the outdoor air is cooler.

a. Co Creation Centre with the PCM-battery in the Climate Tower

b. Office Lab during the extension process

c. AHU with PCM battery on the Office Lab

Figure 1: Buildings at the Green Village are research facilities as well. The Office Lab at the right has much less heat loss than the 6 m high completely glazed Co Creation Centre at the left.

The PCM-battery can be loaded with indoor air in a heating mode when the air temperature is higher than 17°C. The PCM can also be loaded by outdoor air in the cooling mode when the outdoor air temperature is lower than 23°C After evaluation the performance of the first building, it became clear that loading the PCM with cold or hot air via the heat pump is also an attractive option. During the night in summer the outdoor temperatures are lower than during the day. Less cooling will be necessary, the COP of the heat pump will become higher and the electricity prices are usually lower as well. In that period a buffer can be loaded with cold. During the day electricity of photovoltaic panels can be used. This will also reduce the required thermal and electrical capacity of a heat pump, making a PCM battery more economic. The PCM-battery can also deliver cold additionally to or instead of the heat pump [1-3].

A second option for buildings is a water-to-PCM battery with a phase change temperature of, for instance, 44-48°C. In winter the PCM battery can be loaded with heat of, for instance, 48°C when the heat pump is not fully in use. This type of battery can be loaded any time, separate from the air-handling unit, when the electricity prices are relatively low during the day. At the moment, in spring and autumn, electricity is even costless between 12:00 and 17:00 h via some energy companies. The type of energy contract determines the best options. A water-to-PCM battery is able to load a battery in a short time, because the energy content of water in J/kgK is 3,500 times higher than air. Combined with comparable low-pressure differences, water velocities can be more than 100 – 500 times lower than air [4].

PCM is also increasingly applied in ceilings and walls. Using a phase change between 20 and 23°C is generally sufficient for summer and winter in a moderate climate. In (sub)tropical regions the PCM is usually only applied for the cooling season. A recent paper evaluates the indoor climate of apartment buildings with natural or hybrid ventilation and uses PCM with phase change peaks for cooling between 25 and 31°C [5]. For light weight buildings combined with PCM there are two ways of CO_2-reduction:

- Less cooling and heating energy.
- Less massive material like concrete which has a high CO_2-demand in its production time.

Air-to-PCM batteries in combination with heat recovery are also evaluated elsewhere and the results are promising [6,7]. In water-PCM batteries the PCM is often enclosed in encapsulated balls [8]. Sometimes, at very high temperatures like 400°C, oil is used instead of water [9]. In that case the oil is heated up direct with electrical heating elements.

Technical Outline of the Systems, Simulations and Measurements

Air-to-PCM Batteries

The next figure shows an example of a PCM-panel with 6 semi-open compartments. The casing is of HDPE-material and the PCM-material is Calcium Chloride Hexahydrate, which is widely used [10].

Figure 2: Example of a PCM-panel in an Air-or Water-to-PCM Battery with 6 semi-open internal compartments

In the Co Creation centre the panels are stored in a battery in a Climate Tower, in fact a different shape of air handling unit. In figure 3 the thermal storage characteristics of PCM Thermusol HD 23 (172 kJ/kg) are presented:

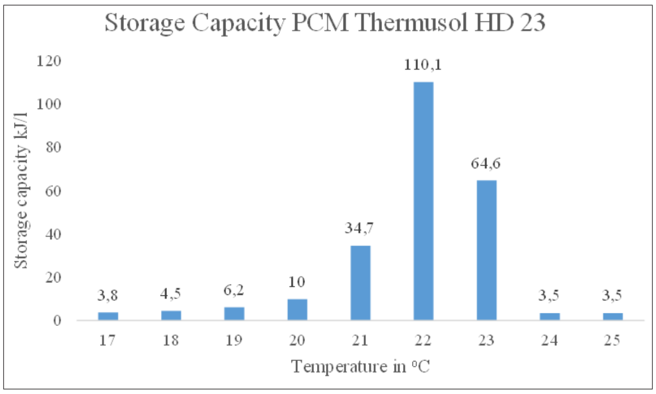


Figure 3: Thermal storage characteristics of PCM Thermusol HD 23

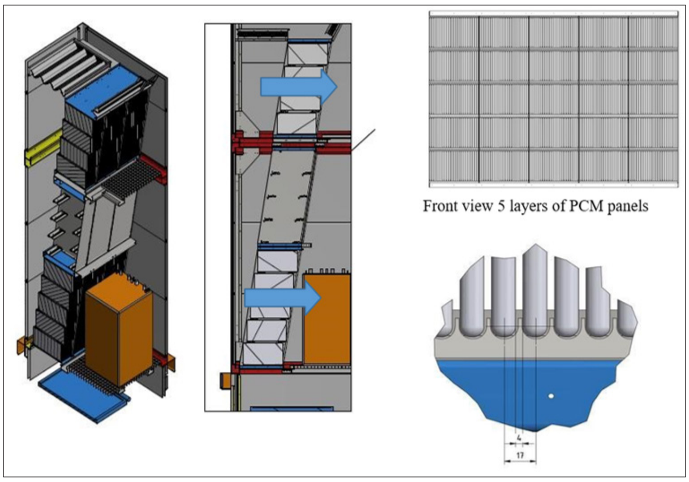


Figure 4: Design of an Air-to-PCM Battery in the Climate Tower with 1,170 Panels and 101 kWh storage capacity. The distance between the panels is 4 mm. Currently the Battery has 1,482 panels with a capacity of 121 kWh. The energy content of the PCM is 172 kJ/kgK (20 -23 °C) or 147 kJ/kgK (17 – 20 °C).

Simulations and Measurements

Most of the theoretical background has already been published in detail and only the main elements are mentioned here [1]. In the following table the (un)loading times and other characteristics of one of the configurations of the PCM battery (phase change 20-23 °C) for different air flows are presented. This is the result of CFD-simulations which have been compared with measurements [1].

Table 1: Results of the CFD Calculations

The air inflow is steady-state but the thermal analysis is transient

Air Flow Condition	h_c (W/m²K)	(un)Load Time (s)	ΔP (Pa)	Calculated Maximum Heat Transfer (kW) at a ΔT of 3°C	Calculated Average Heat Transfer (kW)	Latent Heating / Cooling Per Panel (Wh)	Total Latent Heating / Cooling (kWh)
10800 m³/h, 2.3 m/s, 15 °C	20.4	18000 s (5 h)	21	23	10.3	155	181
7200 m³/h, 1.5 m/s, 15 °C	14.5	36000 s (10 h)	16	16.4	5.2		
3600 m³/h, 0.8 m/s, 15 °C	8.8	64800 s (18 h)	8	9.9	2.8		

The h_C value is based on a calculation, which is close to the value calculated by PHOENICS, based on PCM of 310 J/kgK with an energy content of 172 and 147 kJ/kg the (unloading) time will become proportional shorter.

PCM-temperature measurements of a full year, from November 2023 till the end October 2024 show thermal energy savings of 7,517 kWh when the heat pump produced 23,000 kWh. The thermals savings of heat and cold energy are maximal 25 %. In reality cooling by PCM in the heating season will reduce this saving percentage somewhat (see Figure 5), but it is still difficult to quantify this. The following table shows the savings per month:

Table 2: PCM-Energy Savings in a Year (121 kWh Buffer)

2024		
October	491	kWh
September	706	kWh
August	652	kWh
July	654	kWh
June	637	kWh
May	749	kWh
April	1082	kWh
March	955	kWh
February	504	kWh
January	374	kWh
2023		
December	236	kWh
November	477	kWh +
Buffer	7517	kWh
Heat		
pump	23000	kWh +
	30517	kWh

Most of the savings are in March and April when there is alternating heating and cooling. In December and January the outdoor temperature becomes too low for substantial cooling savings.

In figure 5 the temperatures of the air after the cross-flow heat exchanger and of the PCM are presented. These are derived from the BMS-system of Priva. The PCM realizes extra savings generally upon the heat exchanger that already increases the indoor temperature significantly compared to the outdoor temperature. The PCM can store the internal heat for some time, see an example of the maximum PCM temperature at 3 October.

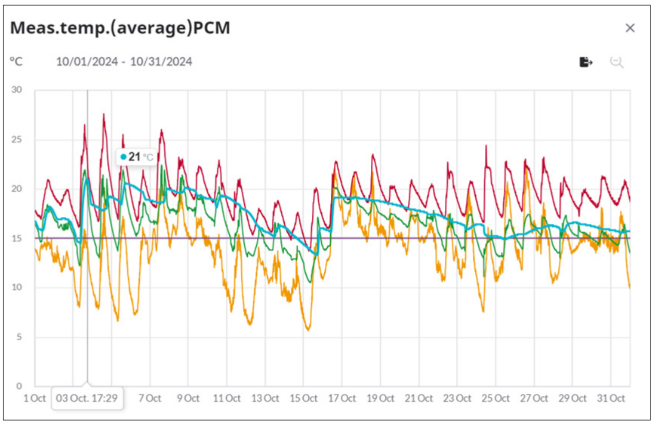


Figure 5: Temperature measurements in October 2024. Indoor Temperatures (Red), PCM Temperatures (Blue), Air Temperatures after the Cross Flow Heat Exchanger (Green) and Outdoor Temperatures (Yellow).

In Figure 6 the BMS-system is presented:

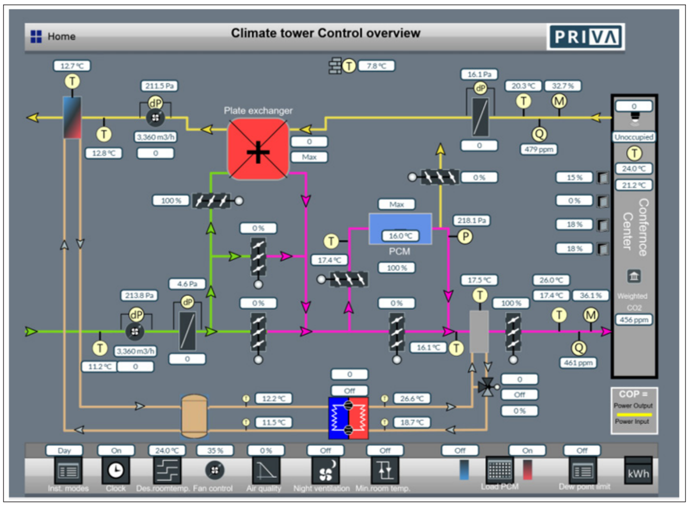


Figure 6: Overview of the BMS-Dashboard. The red box is the Cross Flow Heat Exchanger and the blue box the PCM-Battery

New Developments of the System

The next step in the development has been the option to load the battery via the heat pump. In that case the air is recirculated via the battery in an air handling unit the following design can be used (Figure 7):

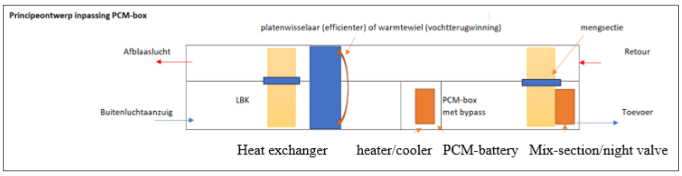


Figure 7: Scheme of an AHU in which the PCM can also be loaded with a Heat Pump and Return Air via a Recirculation Option (at the Right).

Figure 8 shows a technical drawing of an AHU with PCM-battery:

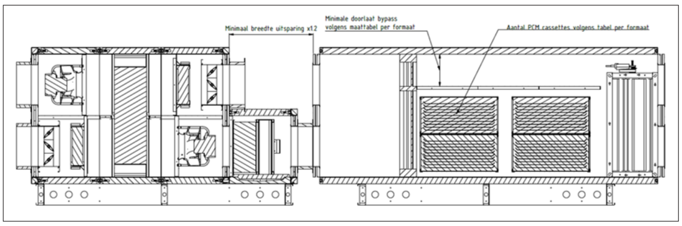


Figure 8: Design of a PCM-Buffer in a more conventional Air Handling Unit. In this scheme Heat Recovery is applied and there is no Return Flow Option within the AHU like in Figure 7. In reality a Cross-Flow Heat Exchanger instead of a Heat Recovery Wheel is applied.

The system of Figure 8 is applied on the Office Lab at the Green Village (Figure 1b and c), which has a light weight structure of wood. It has a much lower glass percentage per m^2 than the Co Creation Centre, because has a much lower internal height, circa 2.6 m, and is deeper. This leads to less heat loss, although this building is also almost fully glazed. The PCM-buffer has 528 panels of PCM20 (17-23 °C,147 kJ/kg) and 264 panels of PCM23 (20-23 °C, 172 kJ/kg). First measurements and calculations show that most of the heating and cooling demand of the 60kWh buffer (17-23 °C) can be delivered [11]. In Figure 10 can be seen that most of the internal heat is saved by the PCM-buffer. The additional active heating is minimized in this way. In Figure 9 the BMS-system is presented:

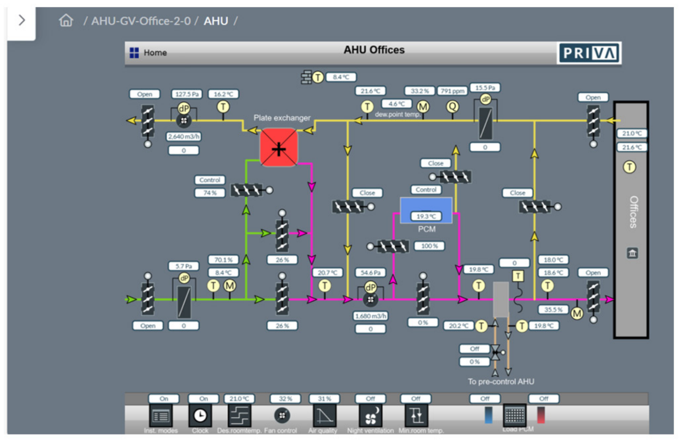


Figure 9: Overview of the BMS-Dashboard. The red box is the Cross Flow Heat Exchanger and the blue box the PCM-Battery

In Figure 10 the temperatures over the month February 2025 can be seen. The PCM-buffer delivers most of the thermal energy.

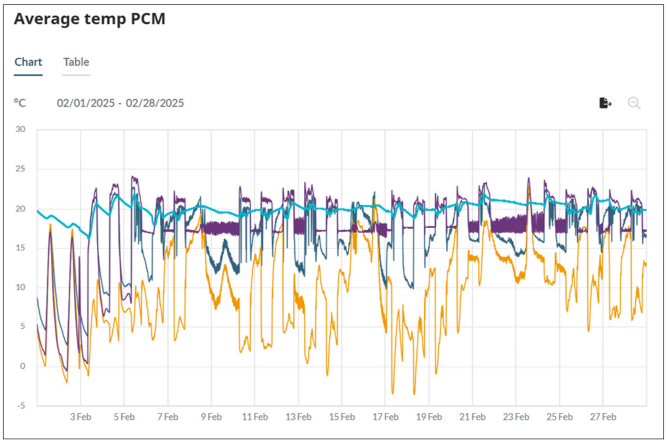


Figure 10: Temperature measurements in February 2025. Indoor Temperatures (Purple), PCM Temperatures (Light Blue), Supply Air Temperatures after the Cross Flow Heat Exchanger (Dark Blue) and Outdoor Temperatures (Yellow).

Water-to-PCM Batteries

Aan alternative additional buffer is a water-to-PCM battery. With this buffer it is possible to improve the heating efficiency of a heat pump making use of the moments during the day when the electricity prices are low or even negative and of PV-energy.

Figure 11: Prototype of a Water-to-PCM-Battery module at the top of a Buffer with 80 mm isolation [12]. The distance between the PCM-elements is 3 mm.

A test with a water-to-PCM-buffer of 55°C and 24 kWh of heating energy (Figure 11) shows that it can be unloaded till 35°C within 55 minutes and 10 litres per min (= circa 0.017 m/s in the buffer). By increasing the flow this time can even be reduced proportionally [14].

A current option on the market is a water-buffer, for example from the Borg-firm: a 4,000 litre water buffer underneath or beside a house (Figure 12) of the new start-up Borg firm can store circa 200 kWh of energy, when the water cools down from 65 to 22°C. However, the external size of 3,80 x 2,90 x 1,60 m (= 17,6 m^3) makes is difficult to install it in an existing situation, but not underneath a new building and outdoors [13]. In this case 83 % of the size is isolation (for 1 % energy loss per day) and rest-space. For a diurnal storage not so much, isolation will be necessary. However, the development and application of this buffer is delayed because the control-system of loading and unloading warm water in combination with heat-pumps needs more attention. For instance, there are many different in- and output communication protocols of heat-pumps. On top that, the original idea was a zero-pressure connection with the buffer. When the buffer is underground or cannot be reached no maintenance is possible. In the future the buffer will connected with a pump that will be strong enough to integrate the system in a heating or cooling circuit. All the elements that may need maintenance will be outside the buffer.

Figure 12: Image of the installation of a Borg-Buffer in a garden at the Green Village

One of the advantages of an air-to-PCM compared to a water-to-PCM buffer is the relatively low weight and the high energy content at lower heating temperatures like 35 or 45 °C. The size of a battery also depends on the amount of isolation around the battery. The thickness of the isolation depends on the time that the energy should be stored: a few hours, a day, a few days, a week or longer. Underneath the Co Creation Centre both buffers will be tested.

For an air-to-PCM-battery with 1,300 panels (CSP 275, HD 23, 172 kJ/kg) and circa 100 kWh storage capacity 2,100 kg will do. In the following table the characteristics of an air- or water-to-PCM-buffer and a water buffer are compared:

Table 3: Storage option for water or PCM-Buffers. The supply water temperature is 55 - 65°C or higher
The minimum water temperature is 22°C (Borg) or 45°C (Orange Climate)

	Storage Medium	Casing PCM/ Outside	Storage Capacity	ΔT	Weight	Size Internal	Size External
Borg	water	EPDM, EPS200, 300 mm around buffer	200 kWh	43 K	4000 kg water + casing	4.00 m^3	3.8 *2.9 *1.6 m =17.6 m^3, within EPS circa 14 m^3
Orange Climate	PCM52, air-to-PCM	HDPE, 80 mm around buffer	200 kWh	7 K	3600 kg PCM	5.0 m^3	6 m^3
Orange Climate	PCM52, water-to-PCM	HDPE, 80 mm around buffer	200 kWh	7 K	4800 kg PCM including 1200 kg water	4.8 m^3	6 m^3
Flamco	PCM70, water-to- PCM	Vacuum isolation panels	10.5 kWh	7 K	110 kg PCM + x kg water	unknown	0.18 m^3

The advantage of PCM52 is the high storage capacity within a 7 K phase change temperature zone between 45 and 52°C. Because of the relative low energy content of PCM of 2,100 J/kgK in a solid or liquid phase, water with an energy content of 4,200 J/kgK is more effective outside the phase change temperatures. However, PCM has a 35 % lower weight for the same energy content.

In the Co Creation Centre, one of the two buildings that is evaluated, the maximum temperature via the heat pump is 50°C, making PCM48 here a more logical choice. In this case the crystallisation temperature is 44°C. In that situation storage in water is not very efficient anymore. The ΔT between 48 and 22°C is 26°C. Of the storage capacity would be (48-22) / (65-22) = 60 % left. On top of that, with a ΔT of 4 the storage capacity of PCM with 195 kJ/kg is more than 10 times higher than water. PCM-materials are more effective at lower heating temperatures, because the phase change storage capacity does not change at lower temperatures.

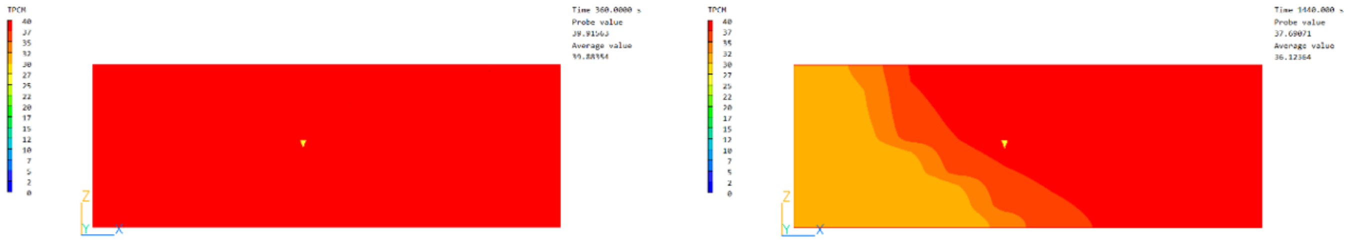
One of the research-aims is to evaluate the application of small modular PCM-storages that are easy to integrate in a building. A disadvantage of this choice is still the high investment per kW or kWh compared to a large buffer like the Borg water-buffer.

The mutual position of the PCM-panels is also an important parameter to consider. Are they positioned parallel to each other or in series? The first example is presented in the Climate Tower of the Co Creation Centre (Figure 4). When there is a parallel position and there is a high air flow over the panels a high thermal capacity is possible which also can be seen in Table 1.

Simulations

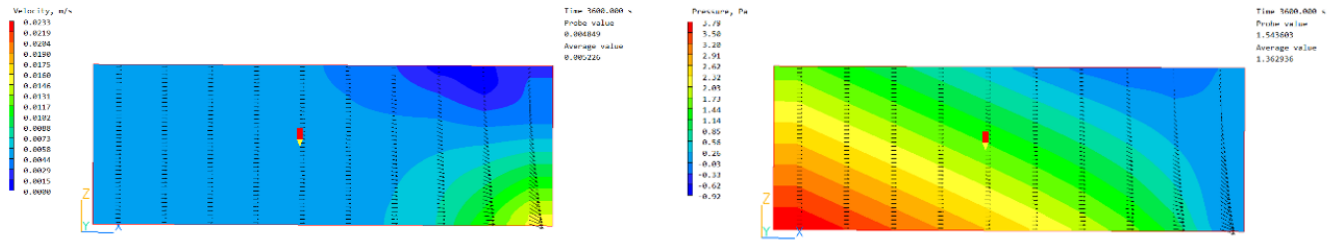
With a (partly) position in series in water the capacity seems to be more limited, but this can be compensated by the volume of the flow. For water this is easier to solve because of the very low velocities. In case of separated water-buffers a parallel position is preferred, but is more expensive. In that case it is easier to reach the maximum capacity during a limited time.

Because the temperature of a PCM-battery drops in relation to the phase change temperature, the capacity (Δ T) will also become lower, see the CFD-simulations in Figure 13:



Average temperature after 6 minutes: 40 °C

Average temperature after 24 minutes: 36 °C



Water velocity in the water-PCM buffer: 5 mm/s

Pressure differences in the buffer: 1.4 Pascal

Figure 13: CFD-Results (Phoenics): Temperatures velocities and pressure in a Water-PCM Buffer. This simulation shows the boundary conditions for the design of a 10 kWh PCM Buffer. The size of the panel is length x with x height = 570 x 13 x 275 mm

The results of the Measurements and CFD-simulations have been used to develop excel-calculation programs for air to PCM as well as water to PCM systems to predict the capacity and loading and unloading times [11,14]. The energy transfer can be predicted by considering PCM as solid within the Phase Change temperatures with a very high energy content per degree K [1]. Buoyancy effects in the panels can be neglected.

Discussion

For heating or cooling purposes, a high storage capacity in kW has only sense when this can also be transported to the occupancy zone via an air or waterflow and a heat exchanger with the same capacity. Usually, the heating and cooling capacity of the heat-pump is the value that should be reached. A storage should be able to take over the heat pump for some time.

In all the considerations the return of investment seems to be a decisive issue at the moment. That is why this is discussed here in more detail, but there is still no final answer. This is influenced by the following parameters:
Price per kWh

The electricity price per kWh is a dominant parameter for economic considerations.

- The advantage of a thermal buffer is that there is much freedom in the choice of time when loading is favourable. So the most favourable moment of the grid can be used.
- On top of that the energy of photovoltaic cells can always be used in a period when there is a heating demand combined with sufficient solar energy.

Investment and Pay-Back Time

It is not always possible yet to say when a buffer is economic attractive or not. It depends on many factors which cannot always be quantified. It also depends on de value that is connected to sustainability. On top of that not only product costs are relevant, the costs of installation should also be taken into account. The focus of this section is just to develop an idea of a reasonable return of investment, which is illustrated by a few basic calculations.

- With a thermal savings are 7,517 kWh (Table 2), an original COP of 2 of the air-to-air heat pump and an assumed electricity price of € 0.20 per kWh the yearly savings are € 750,-. This would lead to a return of investment of 24 years at a price of € 150,- per kWh and an investment of € 18.150. However, the higher the COP of the heat pump the longer the return of investment. On the other hand the price per kWh can be higher when the battery is loaded directly by PV-cells or at moments with even negative electricity prices. This basic calculation example shows that many factors are important to make a positive decision for application.
- When the costs per kW of a PCM buffer are comparable with a heat pump and the expectation is that the heat pump is not necessary during a certain period of time the return of investment is short. In that case the connection to the grid can be reduced as well leading to more savings.
- It is important to know what the maximum heating and

cooling demand is, which determines the capacity of a heat pump. A limited cooling demand of circa 80 % of the heating demand of the heat pump is recommended for warm water-PCM buffers in order to be able to reduce the capacity of a heat pump.

- The investment costs for a small size heat pump with integration and ground buffer are around € 3000,- per kW. A water-to-PCM buffer should have a lower investment per kW to become economic attractive.
- Current prices on the market for water-to-PCM buffers are € 460 per kWh (Flamco information begin 2025), but for a wide application this can become lower. The Flamco and Borg buffer has a relative high temperature in order to prevent legionella infection risks. This is necessary when the buffer is used for potable water as well. This increases the usage opportunities and reduces the pay-back time.
- The water-buffer of Borg of 200 kWh requires an investment of € 14.000,- (information June 2023), including control-systems. This is € 70 per kWh, making it a very attractive alternative.
- For air-to-PCM buffers connected to an air-handling unit the investment should become around € 150,- per kWh and € 1500,- per kW to become economic attractive, this is comparable with the costs of an air-water heat-pump of limited size.

In the following table some current prices and capacities of buffers in The Netherlands are compared. The focus is on water, water-PCM buffers and an electricity battery:

Table 4: Buffers from different companies in the Netherlands

	Type buffer	Size buffer	Temperature	
Orange Climate	PCM (Prototypes)	10 kWh	44 - 48 °C	€ unknown
Flamco	PCM	10.5 kWh	58 - 70 °C	€ 460,- per kWh
Borg	water	200 kWh	65 °C	€ 70,- per kWh
Zonneplan	electrical	20 kWh	-	€ 440,- per kWh

However, not only the price per kWh is relevant but also the CO_2-footprint of the material. This is much higher for an electrical battery than for a thermal battery.

The current electricity usage of the heat pump for heating and cooling of the Co Creation Centre (Table 2) is 11,500 kWh and 23,000 kWh thermal energy with a COP of 2 at the time of the measurements. If 5,000 kWh of equivalent electrical energy could be delivered by a water-to-PCM buffer, taking into account € 0.20 per kWh saved electricity, the total savings per year would be € 1,000. With a return of investment of 10 years the maximum investment of the PCM-buffer could be € 10,000, which is still too low for a water-to-PCM 200 kWh buffer and a return of investment within 10 years, this would become 40 years at an ambitious price of € 200 per kWh. Currently the average electricity price in The Netherlands is € 0.30-0.35 per kWh, including taxes and grid-connection costs, so when the electricity would be generated by PV on a self-sufficient location a1.5-1.75 higher maximum investment could be possible, but this is only on a few locations an option. Taking also into account the reduction of the investment of the capacity of the heat pump including grid connection, the higher COP of the heat pump and reduction of the grid congestion it could become economic interesting. On the other hand, when it is combined with heat storage in the ground with a higher COP of the heat pump local storage becomes less attractive.

Conclusions and Recommendations

- Both air- and water-to-PCM batteries can save energy and reduce the CO_2 footprint of a building and reduce grid congestion.
- When the size of a heat pump can be reduced proportionally to the capacity of a PCM buffer the following conclusions can be drawn:
    - o If the costs of air-to-PCM buffers are comparable with air-to-water heat pumps, it is economic feasible to apply this when the size of the buffer is large enough to replace the heat pump for sufficient time.
    - o If the costs of water-to-PCM buffers are comparable with water-to-water heat-pumps, it is economic feasible to apply this when the size of the buffer is large enough to replace the heat pump for sufficient time.
- When the electricity is delivered by PV the return of investment will become more favourable.
- Hot water buffers (65°C) are an attractive alternative for PCM-buffers, so a cost-benefit analysis is always necessary.
- A water-to-PCM-buffer can, for instance, deliver 200 kWh energy but with a much lower supply-temperature of 45°C and a lower ΔT of circa 4 K. This will lead to a higher COP for the heat pump and has a favourable effect on the return of investment. The low difference between the supply and return temperature will make it also easier to integrate in the heat supply part of the installation.
- More reduction of the costs of PCM buffers are necessary to reach an economic level, although there is already hot water to PCM buffers of € 460 per kWh on the market.
- Electrical batteries have currently almost the same price per kWh as water to PCM buffers but the CO_2-footprint of the material should also be taken into account.
- The costs can be reduced by mass production.
- Large PCM buffers are more economic than small ones because of the lower costs per kWh and when they fit in the total energy balance (daily or weekly) of a building at the same time.
- The size of the buffer should at least fit in the diurnal heating and cooling demand (not too large, not too small). When it is economic larger buffers are an option.
- The costs can also be influenced by sustainability subsidies to overcome the current stagnation.
- It is recommended that an intelligent BMS-system is applied that makes use of low or negative electricity prices, high indoor temperatures in the heating season and low outdoor air temperatures in the cooling season. In the buildings presented here weather forecast and learning from the past to minimize energy consumption is used (Model Predictive Control). For PCM-buffers special algorithms have already been developed making use of low electricity prices. However, making

optimal use of continuous changing prices on the electricity market is still a challenge for the future [15].

Data Availability Statement

The data is only restricted available via the researchers because this is stored via two BMS-systems of Priva at the Green Village of the Delft University.

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