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Delivered		
Author(s) Name	Organisation	E-mail address
Yosr Allouche	NTNU	yosr.allouche@ntnu.no
Silje Smitt	NTNU	silje.smitt@ntnu.no
Armin Hafner	NTNU	armin.hafner@ntnu.no

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1. PREFACE

A dedicated section on the project website will hold the educational material – including manuals, guidelines, books, case study files for computational software and other material – and allow for a basic filtering of information for easy access of website users (available also in South European languages). The material, developed by all project partners throughout the project will be made available as free downloads and for direct integration into supranational, national and regional conferences and workshops. Educational and knowledge-building promotional material presented will be a direct result from the MultiPACK project activities but might also list other case studies and material in line with the project's core ambition to familiarise the HVAC&R market stakeholders, as well as legislators and the wider public, with available efficient integrated heating and cooling solutions. Specific material will also be developed for addressing individual target groups, taking into considerations their peculiarities, as for example, in the case of big supermarket chains, small family-owned shops, hotel chains, public institutions.

The present deliverable includes all the contents of the second educational e-book about MultiPACK. The actual e-book, with the correct design and formatting, can be downloaded from the Downloads section of the project's website.

2. INTRODUCTION [1]

Thermal energy storage (TES) is a technique used to balance the mismatch between the energy availability and demand. Thermal energy storage is essential in applications where the energy source is intermittent or there is a significant lag between energy availability and usage. A thermal energy storage unit (TES) can be identified as an instantaneous supplier when the need for energy is immediate. During those periods when the available energy is higher than the consumption, the storage unit is charged. In contrast, in those periods when the energy available from the primary source is smaller than the demand, the extra energy needed is supplied by the TES through the discharge process. Additionally, equipment size and related costs can be optimised by the "peak shaving" effect of the correct storage design.
The most suitable storage method depends however on the application. During the selection process different aspects such as efficiency, lifetime, capacity and thermal losses should be taken into consideration.
A proper design of TES can have two important benefits. First, it allows for the rationalization of the energy supply capacity by supplying the extra energy demand during peak hours. Second, it improves the cost effectiveness when there is a time shift between energy supply and demand. Thermal energy can be stored above ambient temperatures (high temperature storage) or below ambient temperatures (low temperature storage) depending on the application. Different processes are used for TES: underground, thermochemical, physical and solid medium thermal storage, depending on the operating temperature range. Physical processes are the most used methods and can be classified into sensible (SHS) and latent heat storage (LHS) units. They are generally simpler than chemical methods which use reversible endothermic/exothermic chemical reactions to store or release heat, respectively. The storage media is selected in terms of the operational temperature range of the application. For sensible heat storage, water is a commonly chosen material as it is widely available and has a lower price compared to other materials, additionally, water has one of the highest specific heats of any liquid at ambient temperatures. For latent heat storage, phase change materials are applied, they are characterized by a high energy density over a small temperature range.

2.1. Sensible heat storage

Sensible heat storage is the most applied method for thermal energy storage. This process consists of storing heat by changing the storage medium temperature from an initial temperature (T_i) to a final temperature (T_f) without undergoing a phase change. The stored energy (Q_s) is calculated based on the mass of the medium (m), its specific heat capacity (C_p) and temperature variation (dT) as:

$$Q_s = \int_{T_i}^{T_f} mC_p dT = m \times \overline{C_p} \times (T_f - T_i)$$

Depending on the application, sensible heat can be stored in solid or in liquid phase. Table 1 shows some physical properties of commonly used SHS mediums. It can be clearly seen that water has the highest specific heat capacity when compared to the other materials. This property together with its wide availability and low price make water as one of the most frequently used materials. Other relevant benefits of using water as a storage medium is its non-toxicity and non-flammability. Its practical use is also an advantage as it allows for a simultaneous charging and discharging of the storage tank. Water as a SHS medium can be applied in large scale, e.g. at industrial facilities to store intermittent available energy for shorter periods, or in district heating networks for seasonal storage. The limited use of water for temperatures above 100°C under atmospheric pressure constitutes though its major limitation. In these conditions' oils, molten salts and liquid metals are available [2]. For air heating applications, rock beds and concrete walls are often applied.

Table 1. The most frequently used materials for SHS [1]

Medium	Fluid type	Temperature range (ºC)	Density (kg/m^3)	Specific heat (J/kg K)
Rock	-	20	2560	879
Brick	-	20	1600	840
Concrete	-	20	1900–2300	880
Water	-	0–100	1000	4190
Caloriea HT43	oil	12–260	867	2200
Engine oil	oil	up to 160	888	1880
Ethanol	organic liquid	up to 78	790	2400
Proponal	organic liquid	up to 97	800	2500
Butanol	organic liquid	up to 118	809	2400
Isotunaol	organic liquid	up to 100	808	3000
Isopentanol	organic liquid	up to 148	831	2200
Octane	organic liquid	up to 126	704	2400

The efficiency of sensible heat storage systems can be evaluated by the first-law efficiency as follows [2]:

$$\eta = \frac{Q_{ch}}{Q_{id,ch}} = \frac{T_f - T_i}{T_{ch} - T_i}$$

Where Q_{ch} represents the total amount of stored energy. The ideal amount of stored energy ($Q_{id,ch}$) obtained by assuming that at the end of the charging process, the final temperature (T_f) of the storage material reaches the temperature of the heat source (T_{ch}).

2.2. Latent Heat storage

The latent heat storage consists of using the latent heat of a material to store energy when the storage medium experiences a phase change. The latent heat of fusion consists of the energy transfer during solid-liquid phase change while the latent heat of vaporization consists liquid-gas conversion. Commonly, the latent heat of vaporization is higher than the latent heat of fusion, nevertheless the former process implies a large change of the specific volume. This large volumetric change is not favourable when it comes to technical challenges on the tank design, moreover the system would require a larger equipment size because of the low density of the materials in vapor phase. As a result, for technical and economic considerations, the solid-liquid phase change materials are more convenient for heat storage devices. LHS are characterized by a high energy density for a small temperature change when compared to SHS [3]. The total amount of heat stored (QLHS) is equal to the enthalpy difference (ΔH) between the beginning and end of the phase change. Assuming a non-isothermal process, it can be expressed as follows:

$$Q_{LHS} = m\int_{T_i}^{T_{pc}} C_s \, dT + mL + m\int_{T_{pc}}^{T_f} C_l \, dT$$

Where T_i, T_{pc} and T_f represent the initial, phase change and final temperature of the storage medium, respectively. C_s represents the specific heat of the material in solid phase while C_l corresponds to the specific heat in liquid phase. L is the latent heat of phase transition.

3. MOTIVATION AND BENEFITS BEHIND THE INTEGRATION OF TES

There are commonly three main sources promoting and highlighting the need of applying thermal energy storage: the energy control and utilization, the end-user and the environment. Indeed, TES corrects the mismatch between the energy availability and demand: In fact, a thermal energy storage unit can be identified as an instantaneous supplier when the need for energy is immediate. It is essential in applications where the energy source is intermittent (solar/wind source) or if there is a significant lag between energy availability and usage. Additionally, equipment size and related costs of the system where TES is applied, as e.g. in refrigeration, can be optimized by the "peak shaving" effect of the correct storage design. Those peaks are characterized by high electricity cost compared to the other periods, and thus extracting energy from the storage unit is many times more economical. TES represents a very important benefit when applied to thermal systems: in one hand it allows for the rationalization of the energy supply capacity by supplying the extra energy demand during peak hours. In another hand it improves the cost effectiveness when there is a time shift between energy supply and demand.
Benefits on the energy control and utilization have a direct and positive impact on the end-user as the latter take advantage of:

- A Reduced initial cost offered by the optimized (reduced) capacity of the equipment. This generates automatically lower maintenance costs for the user.
- An improved indoor air/water quality mainly for TES units integrated into AC systems.
- An increased flexibility due to a wider availability of the energy covering peaks and non-peaks hours.
- Space optimization thanks to the reduced equipment size.

Last but not the least, environmental concerns represent an important source of motivation to consider the integration of thermal storage into the thermal systems. TES contributes to a reduced pollutant emission that can be achieved through the promotion of renewable energy sources which leads in turn to the conservation of fossil fuels. There is also another aspect to save the environment; the decrease of Greenhouse gases emissions such as refrigerant leakage from refrigeration systems. As an example: extracting energy form the cold storage unit means a steadier state operation of the refrigeration unit and thereby the refrigeration system has a longer lifetime and has fewer refrigerant leaks.
A common question regarding TES units is frequently asked: what is the most important benefit of a TES system? A common answer is that TES ensures peak shaving by shifting the peaks characterized by high energy costs to periods characterized by low energy cost. In this case, the off-peak electricity capacity is used to both produce and store energy for a later use. Another important benefit is then observed as TES results in an increased supply capacity during high energy demand periods. This process will lead then to the installation of smaller production units which allows the end user to save the primary costs.
More benefits are often reported in parallel to cost saving as the performance optimization of cogeneration power plants which are commonly characterized by an over generation of electricity during periods of low electricity demand which in turn increase the system reliability and viability.
The system reliability is also increased when using TES as the system can efficiently operate and complete its function using the storage under different operating conditions: such as blackout, failure in the heat pump units, service periods, etc. The utilization of the surplus heat from a refrigeration cycle for example is another benefit to report as it improves the cycle efficiency in one hand and provides a connected auxiliary HVAC system which supplies energy from the recovered and stored heat.
TES is a reliable application in industrial refrigeration facilities where the demands for thermal energy is characterized by large peaks during specific periods of the day. This variable energy demand profile is also observed for hot water consumption, AC cooling and certain industrial processes. Figure 1 illustrates a typical hot water consumption curve where no storage tank is applied (Figure 1.a) and an alternative method applying a TES unit to satisfy the energy and power needs during the peak periods (Figure 1.b). In Figure 1.a, it can be clearly seen that the hot water production implies the same energy (hot water) consumption profile independently of the energy costs and peak power consumption. Figure 1 b) depicts the accumulation of hot water into a TES unit. The power intensity of the supplied heat is reduced and stabilized by the buffer effect that the storage provides. This allows for an optimized and efficient

operation of the vapor compression system. In addition, equipment investment costs are reduced in case b), as the size of compressors and heat exchangers can be significantly decreased.

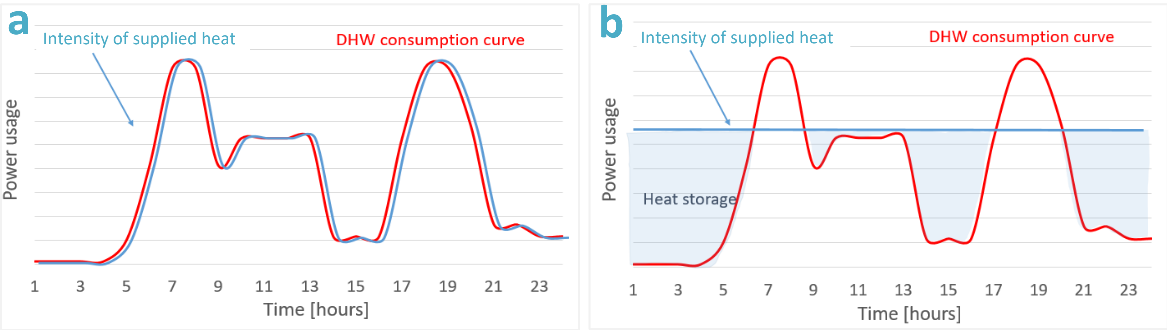


Figure 1 Hot water consumption and accumulation curves without (a) and with (b) thermal storage.

3.1. Integration strategies of thermal energy storage

Figure 2 illustrates the common operational strategies of TES. They are generally classified into full or partial storage [4]. The full storage is the approach where the storage meets the total peak period needs (Figure 2.a). Its operation consists of the load shifting of the entire load peak to off peak periods. It is generally recommended for high peak electricity costs and results then in high costs saving, but in the same time it would require high initial costs since new equipment are added to the refrigeration system e.g. the storage unit, the storage medium, the connections between the refrigeration system and the storage unit ..

The other way of storage is the partial storage where the storage meets a part of the peak period needs and the chiller meets the rest. Partial storage can be achieved by the load levelling (Figure 2.b) or load limiting approach (Figure 2.c). The Load levelling approach consists of operating the chiller at full capacity 24h. The surplus of energy is stored when the cooling load is lower than the cooling capacity, and when the Load is higher than the chiller capacity, the storage meets the load. The load limiting approach consists of operating the chiller at a reduced capacity during peak hours, the storage controls then the facility peak demand. This method is characterized by initial costs and savings which are higher than load levelling but lower than those obtained by load shifting. Therefore, the load limiting is commonly preferred as it constitutes a good compromise between load shifting and load levelling approaches.

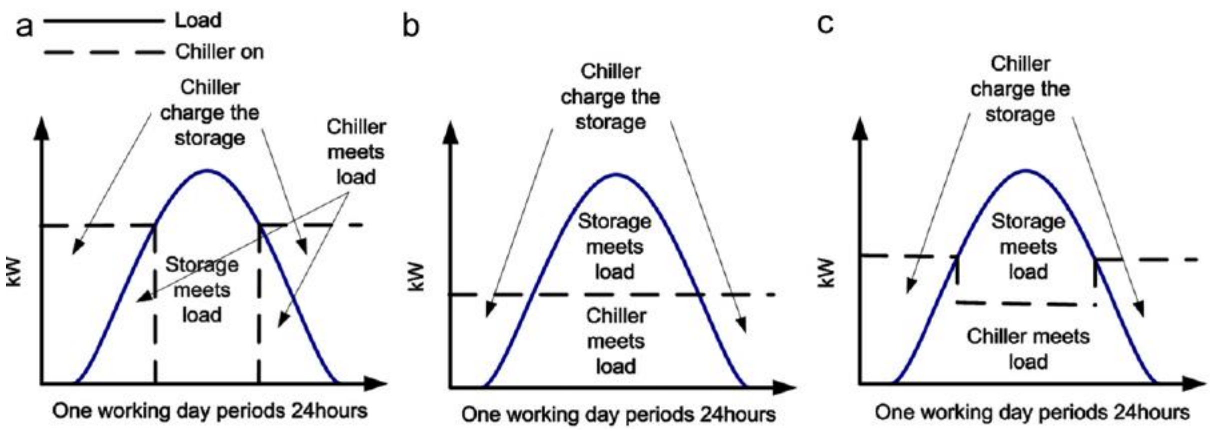
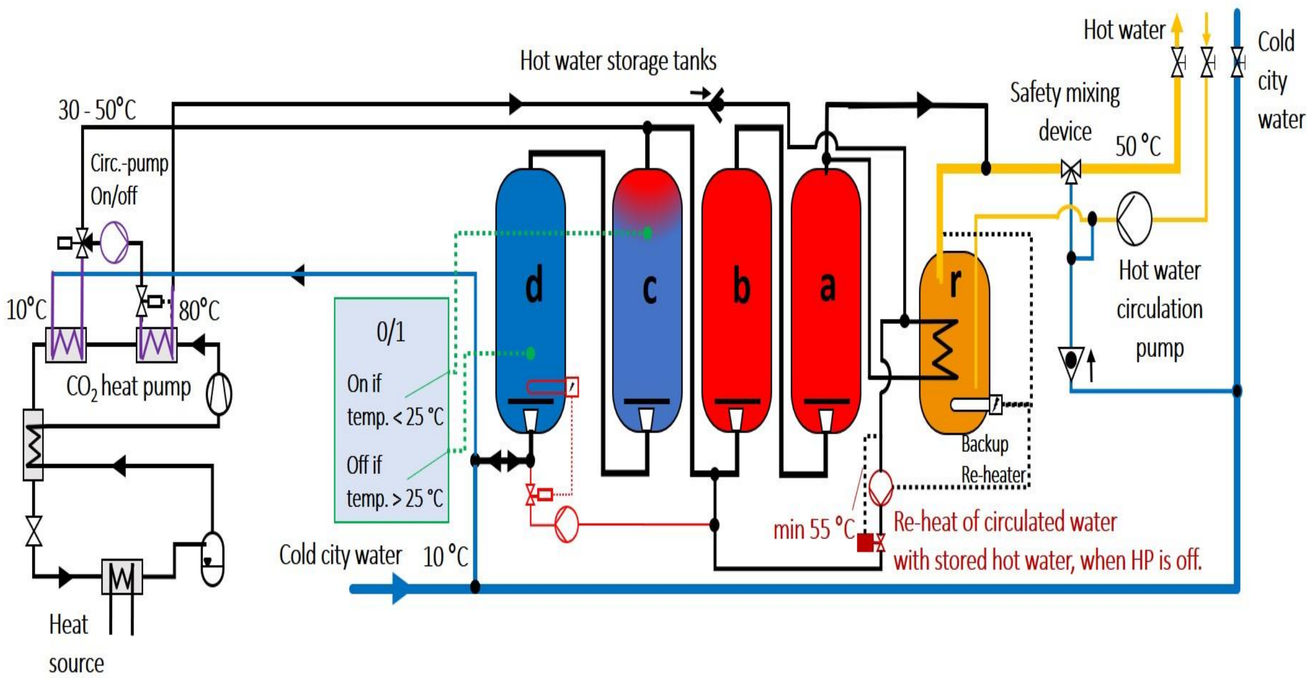


Figure 2 Different storage strategies. (a) full storage, (b) load-levelling storage, (c) load-limiting storage [4].

4. EXAMPLE OF THE INTEGRATION OF A HOT WATER STORAGE INTO A CO_2 HEAT PUMP TO PROVIDE HOT WATER TAP FOR A HIGH ENERGY DEMANDING BUILDING, E.G. A HOTEL

In this section, an example of the integration of hot water storage devices into a CO_2 heat pump for large buildings such as hotels, restaurants, or even large domestic application (multi-family homes) is presented. As previously mentioned, sensible heat storage using water as the storage medium represents the most attractive solution to store heat below 100°C under atmospheric pressure conditions as water is characterized by a wide availability, affordability and high specific heat compared to other SHS mediums. Figure 3 represents a CO_2 heat pump system designed to provide the tap water temperature requirements (50°C) for sanitary use towards the building side. The heat pump is connected to a series of four hot storage tanks through the CO_2 gas cooler. The two last tanks in the series tank (c) and tank (d) represent the storage buffer. The charging process (heat pump on) is induced when this buffer is empty. It generally takes place during the off-peak periods in order to afford the peak hours consumption. In a hotel for example, off-peak periods are those where the hot water consumption is very low or practically inexistent, e.g. between midnight and the early morning hours. The storage is periodically more or less discharged to satisfy the hotel thermal needs (shower, kitchen.). The storage needs then to be charged again for the next day demands according to the specific consumption profile of the hotel. During the charging process, an ON-signal is sent to the heat pump when the temperature in tank (d or c) reaches a certain temperature limit set by the operator (Figure 3.a). Water is then extracted from the bottom of the coldest tank (Tank (d)) and pumped to the gas cooler, where it is heated up and then reinjected again at the top of the hottest tank (Tank (a)) after reheating the circulated water returning from the building. The surface interface between the hot water layer and the cold-water layer in a specific tank is always moving towards the bottom of the tank, and thus water is moved to the next colder tank.
The thermal storage is fully charged when the normally stratified tanks have a high and uniform temperature throughout the buffer, as shown in figure 3.b. An off signal is transmitted to the heat pump when the last tank (Tank (d) in Figure 3.b) reaches the set temperature.

a)



b)

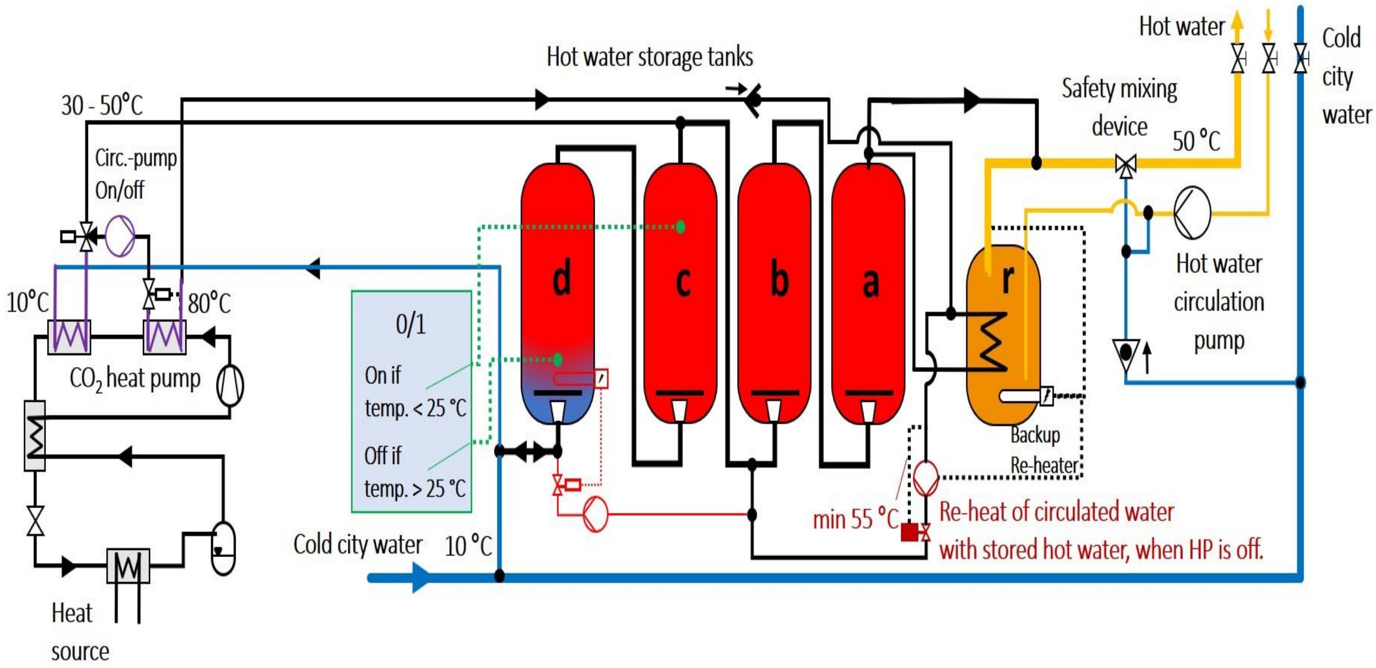


Figure 3 CO2 heat pump with an integrated hot water storage (a) Charging process in progress (b) charging process completed

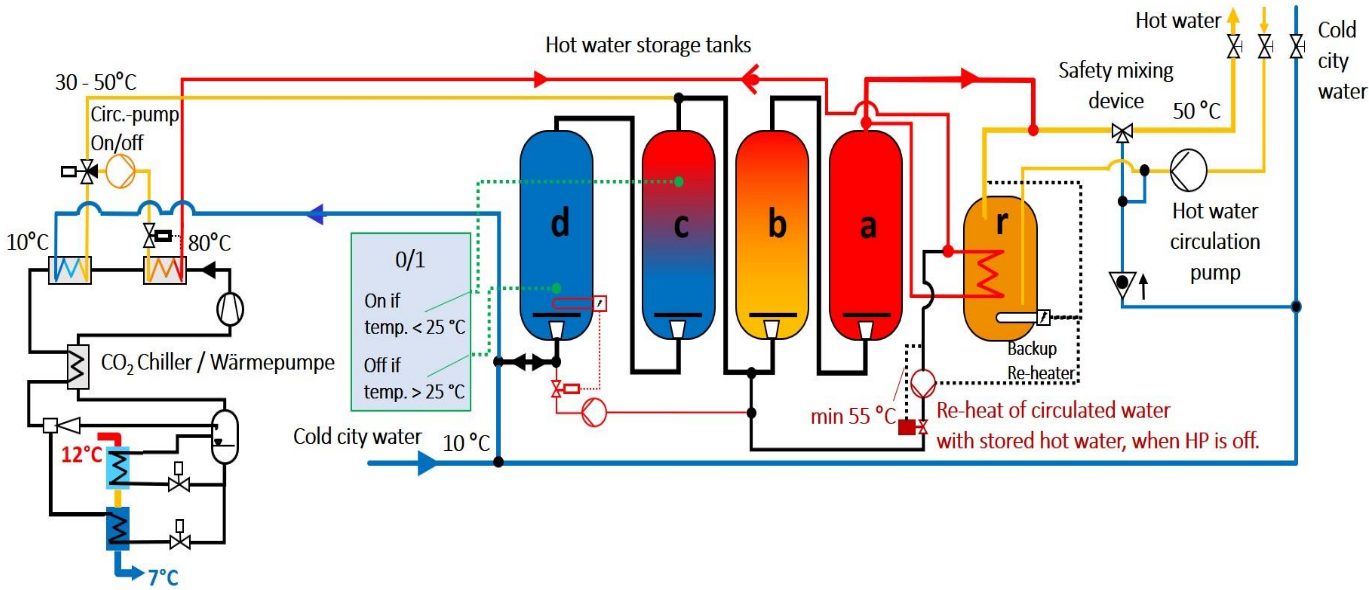
During the discharging process, cold water city must only be injected to the bottom (Tank (d)) via a well-designed diffusor, required at the bottom inlet for each tank, only then the hot water layer is slowly moving towards the top of a specific tank and then moved to the next hotter tank. The hot water to be supplied for usage is extracted from the top of the hottest water tank (Tank (a)) and mixed if needed with cold city water to satisfy a setpoint temperature set by the operator (50 °C) before entering the supply line. The buffer will then again become stratified as the high temperature boundary moves gradually to the right. A reheating tank (Tank (r)) as shown in Figure 3.b is included in order to reheat water in the building return line when the heat pump is off. Heat from the storage tanks is applied to maintain the reheating function.

Just to underline the most important design feature: when using storage tanks in series the preservation of the stratification within each storage tank is of outmost importance. Consequently, the use of storage tanks with a large height-to-diameter-ratio is advantageous as the mixing risk between the hot and cold water layers within each tank is reduced when compared to a low height-to-diameter-ratio tank. Obviously, the most critical period of water layer mixing takes place during the time intervals which are characterized by a high hot water demand as water is continuously extracted from the storage and water is entering each tank from the bottom part. This can importantly affect the stratification in the tank, and thus, in order to maintain the stratification, diffusers must be added into the bottom of each tank.

An important challenge when using a similar design of CO_2 heat pump with storage tanks in series, is handling standstill-conditions i.e. when there is an insignificant demand for hot tap water under both partially-charged (Figures 4.a) and fully-charged (Figures 4.b) conditions. The reheat tank (Tank (r)), needs to be charged in order to prevent a temperature drop in the recirculating supply line within the building. This can be either achieved by a back-up heater integrated in the tank or by using the available energy in the storage tanks, as shown in Figure 4. In this case, a temperate sensor is applied to make sure that the return water temperature to the tanks is at around 55 °C. Hot water from Tank (a) is pumped through the reheat heat exchanger, and then returned to Tank (b) at 55°C. When the less warm water is returned to Tank (b) in the bottom part, the stratification throughout the storage is preserved.

The CO_2 heat pump shown in figures 3(a) and 3(b) is a conventional system with internal heat exchanger. The performance of the CO_2 system can be enhanced further by using ejector as an expansion device as shown in figures 4(a) and 4(b).

a)



b)

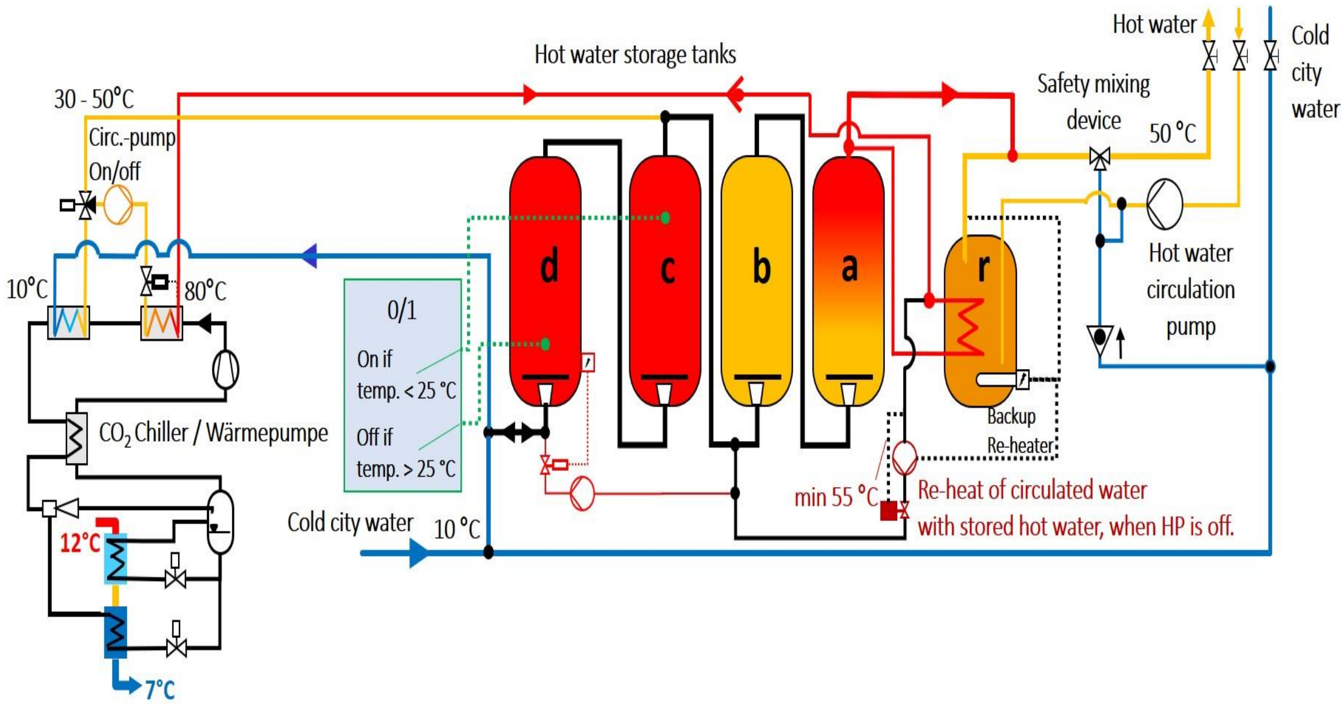


Figure 4 Hot water storage during standstill with reheat of supply-line at (a) partially-charged and (b) fully- charged conditions.

5. CASE STUDY: THE FIRST COMBINED CO_2 HEAT PUMP, AIR CONDITIONING AND HOT TAP WATER SYSTEM FOR A HOTEL IN SCANDINAVIA (HELL HOTEL, TRONDHEIM, NORWAY)

The case study consists of the first combined CO_2 heat pump, AC and hot tap water system integrated in Scandic Hell Hotel in Trondheim, Norway, which was established in 1987. In 2018, the hotel was renovated, a CO_2 heat pump and chiller unit were installed to provide the hotel with its heating (space heating and hot tap water) and AC cooling needs as shown in Figure 5. The system was an upgrade of the previous heating system, which consisted of an electric boiler for base load coverage and oil peak boiler for peak load coverage. This new installation is the first combined CO_2 heating, air conditioning and hot tap water system with an integrated thermal storage for a hotel installed in Scandinavia [5]. The heating capacity of the system is 280 kW. The heat pump design is based on a typical CO_2 single-stage supermarket refrigeration unit equipped with heat recovery.

The CO_2 unit is composed of four parallel compressors where one compressor is equipped with a variable speed drive (VSD) for low load operations conditions. The high pressure and load control of the heat pump is based on feedback signals from the different thermal demands, such as hot tap water, ventilation and the radiators. The CO_2 heat pump is equipped with four 50 kW air/CO_2 evaporators. In case of simultaneous cooling and heating demands, it is possible to recover heat from a chilled water heat exchanger (HX) for AC cooling. The combination of the chiller unit and the heat pump present a double benefit: First it improves the overall system efficiency and second it satisfies the heating needs of the hotel.

Domestic hot water (DHW) can be produced continuously in both preheat and reheat heat exchangers which are connected to a low and a high temperature hydronic circuit as shown in Figure 6. An optimum sized water storage represents a key factor to provide a high system efficiency as the heat pump can operate in optimal conditions to a lager extent. This configuration is especially advantageous in hotel facilities since the hot water consumption curve is characterized by peak hours, as shown in Figure 7. The hot water storage system consists of a set of tanks in series, where the last seven containers of 4.2 m^3 represent the thermal buffer.

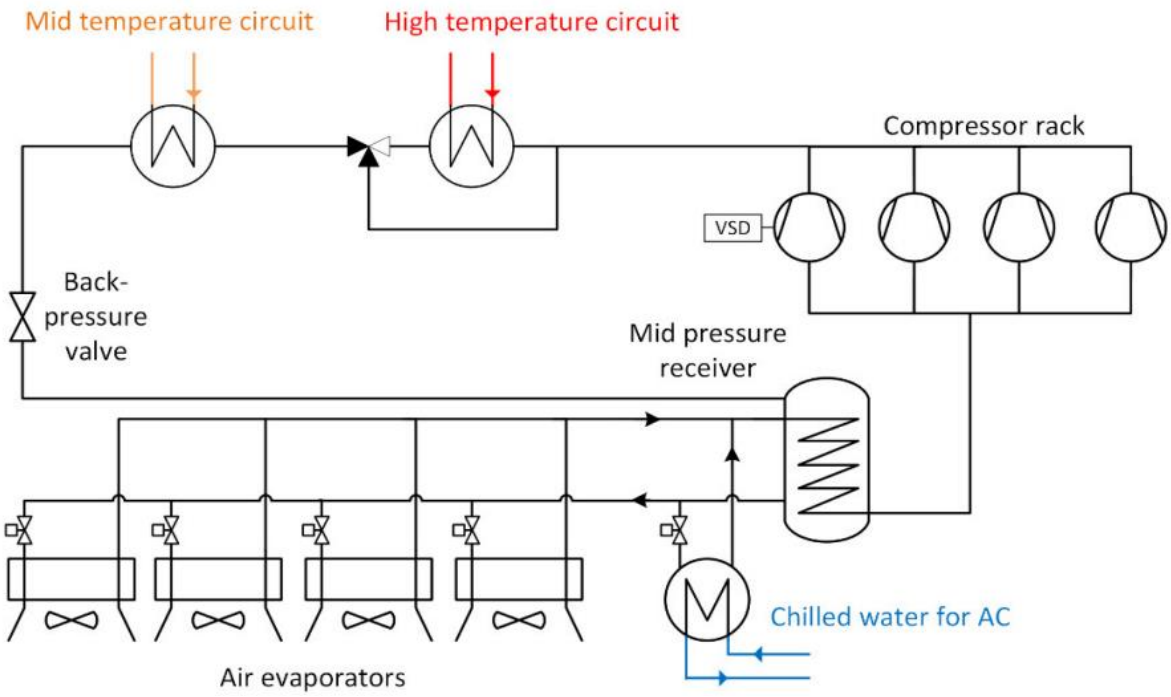


Figure 5 The combined CO_2 heat pump and chiller system installed in Hell hotel, Trondheim (Norway) [5].

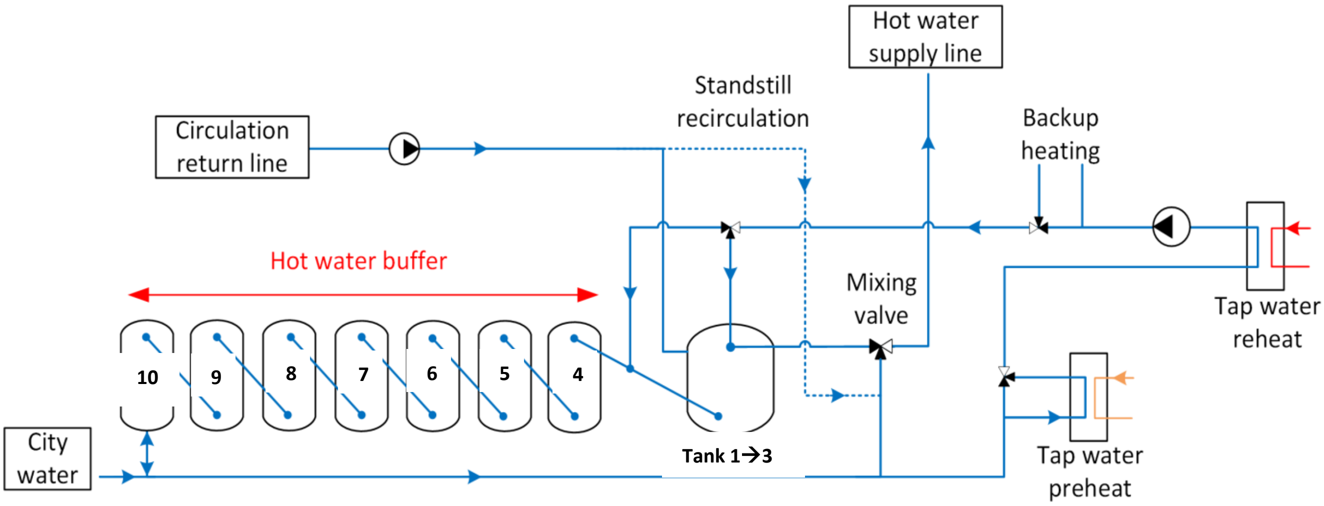


Figure 6 Hot water circuit and buffer storage system [5].

In a hotel, the consumption profile of the DHW depends on the operation of the hotel facilities as well as the guest routine. DHW is used in the rooms, kitchens, laundry services, spa and pool facilities. Figure 7 represents both the DHW average daily consumption profile (DHW_{usage}) and the energy supplied by the heat pump to the storage, (DHW_{supply}), over one-year period. The average daily usage of DHW is 1104 kWh/day. However, significant variations in the daily consumption were recorded with maximum and minimum values of 2480 and 480 kWh/day, respectively. The DHW consumption during the daytime period (from 6 a.m. to 11 p.m.) represents 87% of the daily consumption whereas between 0 a.m. and 6 a.m. it reaches its minimum (18kWh). It can be also seen from Figure 7 that the DHW_{usage} generally encounters daily peaks (around 70 kWh), one in the morning (around 8 a.m.) and one in the evening (around 11 p.m.). For a conventional system without DHW storage buffer, these peaks will generate a high-power consumption, however for a system with an integrated hot water storage, DHW_{supply} does not exceed 58 kWh due to the buffer effect offered by the storage. This shows the ability of the system to handle power peaks on an average basis. The energy storage is depicted by the difference between DHW_{usage} and DHW_{supply} . The storage process is started at 0 a. m. and reaches a minimum value at 6 a.m. The maximum energy stored during the day is calculated to be 22kWh at 8 a.m. at 9 a.m the DHW_{usage} increases up to 73kWh while the storage is empty, the charging process is then induced again and stabilized to a storage energy in the range of 50-55 kWh over the day.

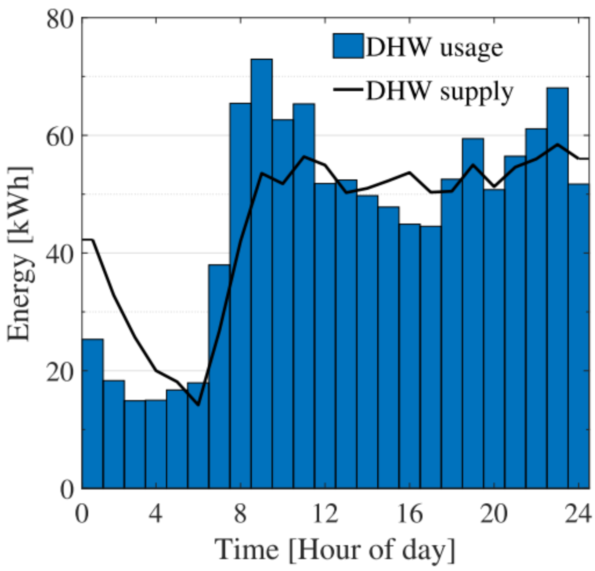


Figure 7 Hourly-average DHW consumption and supply profiles of the hotel [5]

In Figure 8, one can note that the DHW consumption pattern for 5 days period includes large peaks in the range of 200 kW. However, the intensity of energy supplied to the storage is considerably reduced due to the buffer function it provides: In case of hot water generation excess, the heat storage can represent an optimal solution as it offers two important benefits. First, it supplies the extra hot water during peak hours and secondly it allows for continuous accumulation of hot tap water, which stabilizes the compressor power input. It can be also observed in Figure 7 that the buffer in the hot water storage reduces maximum power peaks with 50-80 kW. This illustrates the benefit of including thermal energy storage in vapor compression systems.

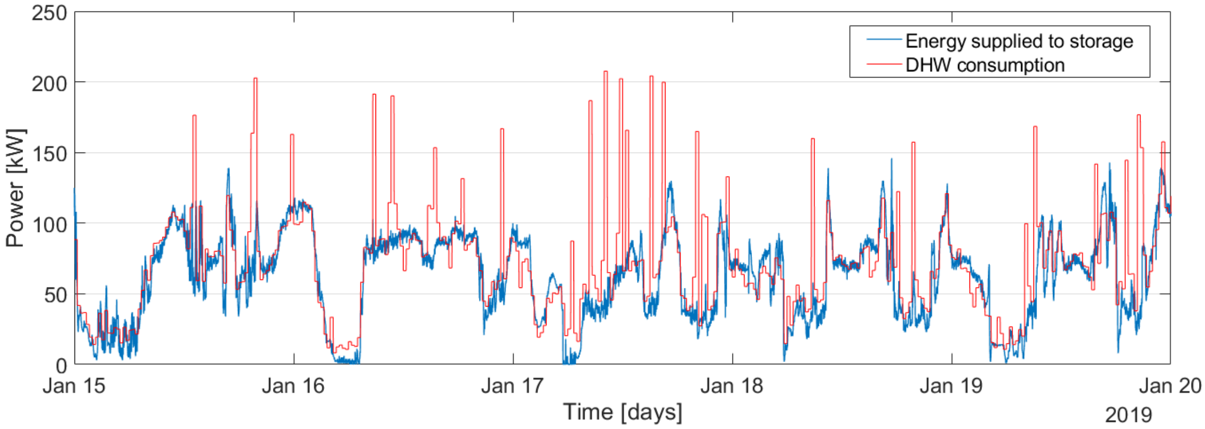


Figure 8 Heat and power supplied to the hot thermal storage over a five-day period [6].

The control strategy of the heat storage is a key factor for a high-performance operation of R744 heat pump and refrigeration systems and a successful stratification in the storage unit. In Figure 9, the main operating parameters of the DHW are represented for 2 days period. The temperature stratification in the storage is depicted in Figure 9.A, where the temperature evolution in tanks 1, 3, 5, 7 and 10 (See Figure 6) are shown. The storage load and energy are also represented in Figures 9B and 9C, respectively. The charging process is represented by the temperature increase across the buffer, and the water interface is moved from the hottest to the coldest tank. Consequently, the temperatures in the middle tanks (Tanks 3–7) can be higher than the temperature of Tank 1 if the hot water supply temperature fluctuates during the charging process. One may also clearly note that the storage temperature is comprised between 8 and 78°C over the studied period. The quality of the storage can be determined by studying the evolution of the temperatures in Tank 1 and Tank 10 which represents the last tank in the series. Obviously, Tank 10 is sensitive to the change in the inlet and outlet mass flow rates of the DHW. During the discharging process (described by the sudden temperature drops in Figure 9A and to the peaks in the DHW usage in Figure 9B), the supply water enters Tank 10 at 8 ◦C and then circulated progressively through the storage as hot water is extracted from Tank 1 to satisfy the hotel needs.
Looking at Figure. 9A, one may note a 24-hour pattern of the DHW storage temperatures. The DHW storage energy is fully discharged and recharged again two times per day. In Figure 9B, it can be observed that the storage is charged for 7–10 h. The sudden drop in the storage temperature can be then related to the behaviour of DHW_{usage}. A large peak of DHW_{usage} peaks in the range of 200 kW generates a rapid decrease in the storage temperatures as seen in Figure 9A. In Figure 9C, it can be observed that approximately 2 hours are necessary to discharge the entire storage during. Also, there is still a daily high demand for DHW at 9 a.m. when the storage reaches its minimum energy potential. The hot water generated by the R744 unit is directly supplied to the hotel to satisfy the large energy demands.

The total energy stored by the end of the charging process is approximately 350 kWh. Although the storage buffer provides a clear reduction in the peak loads. The previous analysis has shown that a storage volume of 6 m^3 is not enough to meet the peak DHW demands of the hotel, mainly in the mornings, as the temperature in Tank 1 drops below its setpoint of 55 ◦C. A proposed alternative to satisfy the energy needs is to increase the water temperature storage in all tanks to 70°C. Under these conditions, the energy storage capacity can be enhanced by about 25%. The use of a larger storage volume can also result in a higher flexibility in the DHW production, which allows for a low-intensity DHW generation over longer time intervals.

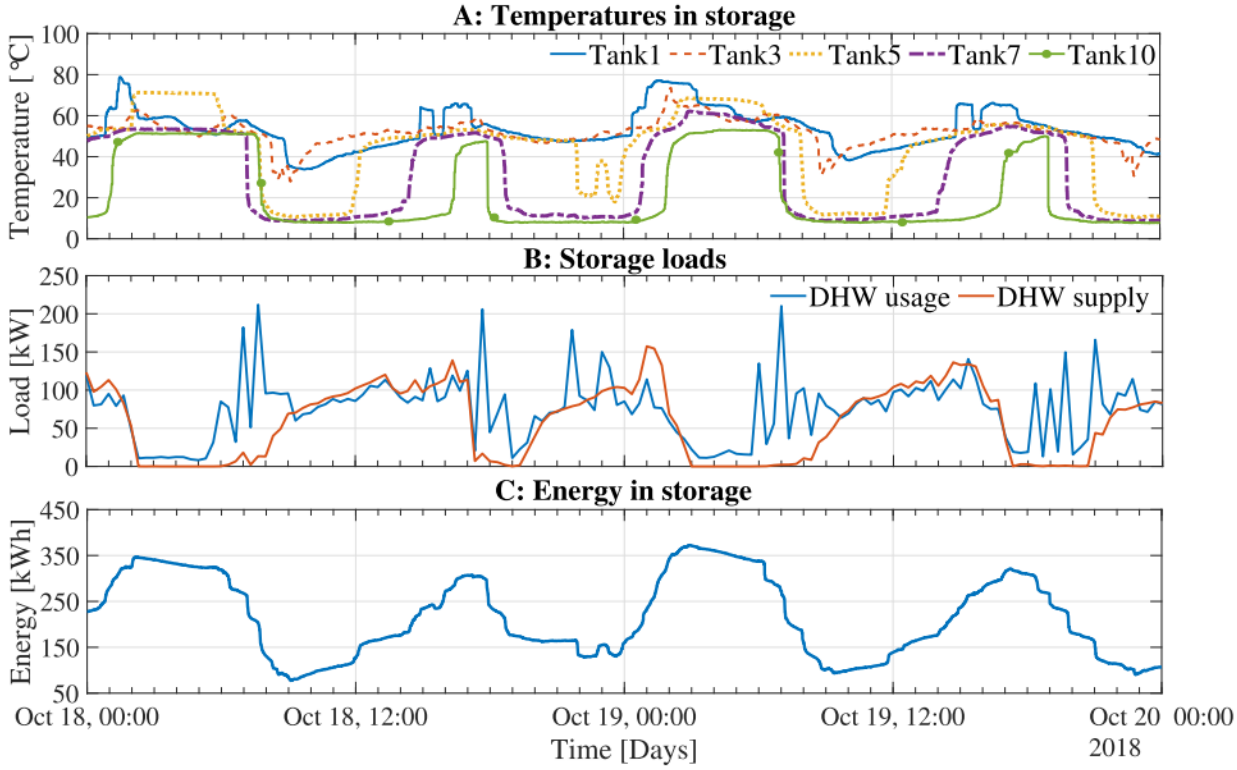


Figure 9 Operational parameters of the DHW system for 2 days period (A) hot storage temperature (B) DHW usage and supply (C) energy storage [6]

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