Energy storage for district energy systems

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7.1 Introduction

The topic of this chapter is large scale thermal energy storage (TES), specifically those used in district heating and cooling (DHC) systems. The decision whether to invest in TES capacity or not within DHC systems depends primarily on an economic assessment. TES technology enables us to balance the supply/demand off-set, e.g., producing when the marginal cost of heat is low and storing it for later use when the production cost is higher, or when additional load (peak load) is demanded from the system.

7.2 What is thermal energy storage?

TES is a device of containment that allows energy, traditionally water-based thermal energy, to be stored for future use, ideally with limited loss.

For the greater part, water is preferred as a storage medium, due to its highly advantageous thermodynamic, chemical, and environmental properties. However, other materials, such as soil, rock, or molten salts, are also used in a variety of TES technologies. The concept of water-based TES implies the use of large insulated tanks or pools, in which a constant water content is sustained (mass-based), independent of energy content.

Thermal stores, also known as heat or chilled water storage tanks, have been used widely in DHC systems as well as domestic heating systems, since the beginning of the 1970s. Today, TES is primarily used in three types of set-up:

1. Short-term storage used in small scale domestic heating systems.
2. Centralized/decentralized short-term storage (for less than ~48 h) used for capacity balancing in large scale DHC systems.

7.3 Centralized/decentralized long-term (seasonal) storage used in large scale district energy systems

The main focus of this chapter is on short-term storage used in larger scale district energy systems. The emphasis is on systems where short-term storage is utilized, as it has been used more widely and is a more established concept. The principles and control strategies commonly utilized in short-term storage are largely the same in long-term storage. Short-term storage used in small scale domestic heating systems is considered to be outside the scope of this chapter.

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7.3.1 Storage types used in DHC

The most common type of TES used in DHC networks is above ground tanks used for short-term storage. This technology is well proven and has found application in combination with a large span of heating sources.

Storage can be either centralized, meaning that they are co-located with a primary energy center, e.g., with a combined heat and power plant (CHP) or an waste to energy (WtE) plant, or the storage capacity can be deployed de-centralized on strategic locations in the DHC network.

In recent years, long-term storage, also known as seasonal storage, has gained ground in the district energy sector, allowing thermal energy to be stored for weeks or even months without significant loss. This is highly applicable when solar thermal sources are utilized in the supply system, as high solar intensity is stored during the summer period when heat demand is relatively low. The primary purpose of long-term storage is the same as that of the short-term storage, however, the design principles are different.

Seasonal storage can be designed as large ponds or pools with a water depth of around 10–15 m and covered by a large insulation cap. This concept is also known as 'pit storage' or 'buried water tank storage'. Other types of seasonal storage are aquifer thermal energy storage (ATES) and borehole thermal energy storage (BTES) (Table 7.1).

7.3.2 Why is TES important?

It is probable that TES will play a pivotal role in future energy systems, due to the increasing share of renewables that these systems must accommodate. With the introduction of more wind, solar, and hydropower, comes a more volatile pricing structure in the energy market, making the selling price of power even more reliant on supply and demand. Integration of storage capacity in a district energy system allows the controller to source optimize, so that the cheapest production unit is fully utilized at all times when available.

Integrating a high share of wind power into our power supply means that large quantities of electricity are produced uncontrolled at times when there is very little demand. One way of utilizing this 'excess power' could be to drive electric heat pumps or refrigeration machines at low cost (in principal anywhere), storing whatever heat or cold there is no immediate demand for, in either long- or short-term TES.

Table 7.1 **Overview of different thermal energy storage (TES) technologies**

Large scale, short term	Large scale, seasonal	Alternative, seasonal
Above ground tank	Aquifer/groundwater storage (ATES)	Concrete
Underground or buried storage tank	Pit storage	Rock caverns
	Borehole storage (BTES)	Pebbles
	Underground or buried storage tank (UTES)	Molten salts (phase change material)

The same principle applies when dealing with large scale solar thermal plants. The highest solar intensity is during the summer months. Unfortunately, this is also the period where heat demand is at its lowest during a year. The obvious mismatch between time of production and time of demand necessitates the implementation of a technology that enables the system to decouple production and consumption; TES will do this.

Within the scope of cogeneration, the main advantage that this particular branch of technology offers is the opportunity to balance the potential off-set between supply and demand, allowing production of heat and power to be decoupled, which is essential when optimization of production cost is a priority. The cost of heat is not only related to fuel cost or operational costs but also on the selling price of electricity. Electricity is sold through a liberalized power market in which the consumer opts to buy from whatever supplier that delivers at the lowest cost, regardless of the source. Installing TES capacity is, therefore, a mean to optimize the power production.

There are two basic cogeneration technologies (with many subcategories):

- The *back-pressure plant* is the simplest method of cogeneration, however, due to the system working with a closed cycle, the heat production is proportional to the electricity production depending on the fuel input.
- The *extraction plant* is a more complex technology that often utilizes extraction steam turbines. This system is more flexible as the operator can increase or decrease heat production but at the same time maintain the level of electricity production. (This is approximate, as an increase in heat production results in a slight decrease in electricity output.)

The control scheme used to optimize production using TES will vary depending on the type of production in question.

As mentioned earlier, it is more common to have the storage unit situated in the same location as the production unit it serves. However, there are examples of storage located out in the network. The purpose of these decentralized storages is generally the same as the centralized storages, and lack of space near the production unit could be the reason for locating elsewhere. In some cases, a decentralized unit can also have the purpose of reducing pipe diameters in the network (cost reduction), although this solution should be carefully thought through, as one wants to avoid a situation where the storage is fully discharged and cannot be charged due to high demand (capacity shortage).

7.3.3 The construction and how TES works in practice

A water-based thermal store can contain water at various temperatures without mixing, thus allowing the energy content of the storage to change while keeping the amount of water constant. Hot water will stay in the upper part of the tank, and the cold will stay in the bottom, due to the hot water having a lower density relative to the colder water. Separating the hot and cold water is a transition zone (also called the “separation layer” or “thermocline”). Inside this zone, temperature varies with a gradient going from the hot water temperature at the top to the cold water temperature at the bottom. Normally, the transition zone is approximately 1 m thick. The concept of separating the hot water from the cold is called ‘stratification’.

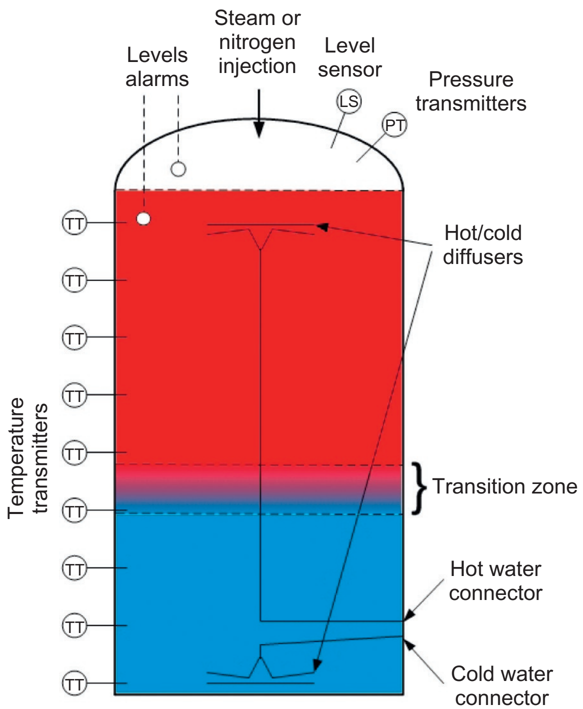

Figure 7.1 General layout of a thermal store.

A hot water thermal store (Figure 7.1) is charged when hot water from the supply line in the district heating (DH) network is supplied to the top of the store through a plate diffuser (top diffuser), while the same amount of cold water is drawn simultaneously from the bottom of the tank (cold water returning to the return line of the DH network). If the design of the diffusers is accurate, the stratification remains intact during charging/discharging of the tank and the separation zone moves up or down depending on whether hot water is drawn out or pumped in. One can consider thermal storage in two ways: either as a consumer (when charging) or as a production unit (during discharge).

7.3.3.1 Diffusers

To avoid mixing of the hot and cold water inside the thermal storage during charging/discharging, it is necessary to install diffusers (see Figure 7.1).

The hot water diffuser is mounted at the top of the tank, while a second diffuser used for charging and discharging of cold water should be installed at the bottom of the storage unit. The diffusers should be designed with the purpose of minimizing inflow turbulence, thus maintaining stable zoning inside the thermal storage.

The flow velocity out of the diffuser should be limited to a minimum, at no time should it reach above 0.04 m/s. Another rule of thumb in diffuser design states that the diffuser plates should never be larger than one-third of the tank's inner diameter.

The storage tank is designed to manage a certain volume flow rate, and the pipes connected to the diffusers should be designed according to this exact flow rate. The piping inside the tank is insulated to avoid thermal transmission. Any heat transfer through the pipe wall induces molecular movement (turbulence), which leads to unwanted mixing inside the tank.

Diffusers can be either fixed or floating. A floating diffuser has the advantage that more tank volume can be utilized, however, this also complicates the pipe design, which means that fixed diffusers are preferred in most cases.

The capacity of a store or the "active volume," can be calculated by subtracting the inactive volume above and below the top and bottom diffusers, respectively, as well as the volume in the transition zone between the hot and the cold zones.

7.3.4 How to utilize TES in DHC?

Introducing TES into DHC systems is a question of optimizing production costs and being able to even out the time mismatch between supply and demand and make operations more flexible. The benefit of utilizing TES may vary, depending on which production plant the storage unit is supporting.

7.3.4.1 CHP plants

As mentioned above, there are two types of CHP technology to consider: back-pressure and extraction plants. TES can be beneficial in optimizing production when dealing with either. The function of the storage is the same, however, there are a few differences in the way they operate.

Back-pressure plants

The main objective of installing heat storage in connection with a back-pressure plant is to allow the operator to produce at full capacity when electricity prices are high (meaning that cost of heat is low). Being able to store heat enables the operator to ignore the current heat demand, which is of particular importance in a system with time variation tariffs.

Extraction plants

Extraction CHP plants have a higher degree of flexibility in operation because heat production can be regulated down in a situation where the heat demand is decreasing. However, in a production scenario, when electricity prices are high, it could be profitable to regulate the heat production down (or shut it off entirely) to maximize electricity production. In this case, the heat demand could be met by supplying heat to the network directly from thermal storage.

During periods when electricity prices are low, e.g., at night, heat can be produced at low cost and stored. As electricity prices increase during the morning hours, heat production can be regulated down, and the heat demand is then met by discharging the energy that was stored in the storage unit during the night time (Figure 7.2).

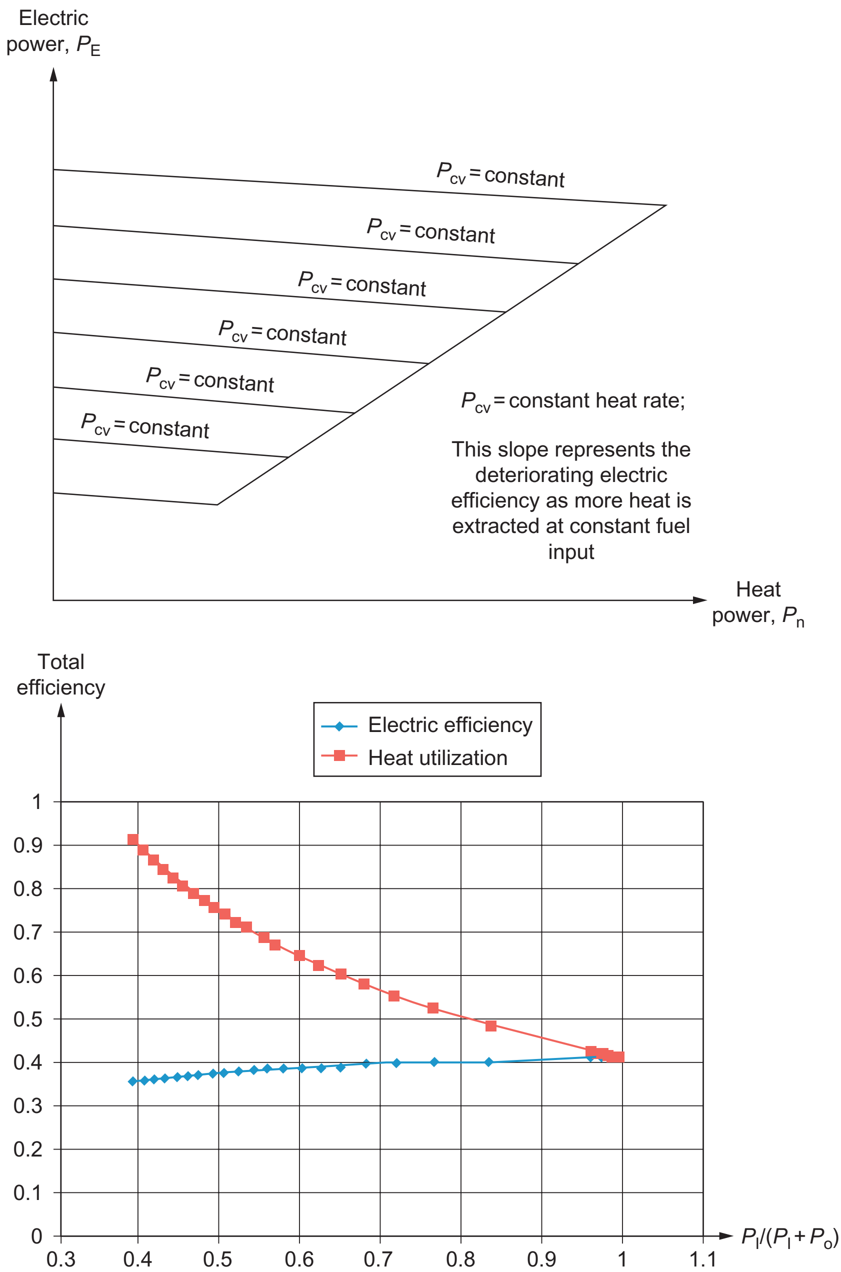

Figure 7.2 Q,P-diagram; typical heat/electricity production ratio in an extraction plant.

7.3.4.2 Waste to energy plants (slow regulating)

Waste incineration waste to energy (WtE) plants are usually extraction CHP, but the fuel is classified as *difficult*, which implies that the plant capacity is regulated less instantly than is the case with gas or liquid fuel-fired plants. When the network is supplied mainly by waste incineration CHP, large fluctuations in demand can be balanced by installing storage capacity.

7.3.4.3 Cooling plants and heat pumps (in connection with solar thermal production)

It has become the norm to combine solar thermal production with seasonal storage to even out the off-set between production and consumption. One of the potential optimizations of such a system is the implementation of a heat pump (or cooling plant for district cooling) to ensure effective utilization of low cost wind power.

Operating an electrical heat pump in connection with solar thermal energy can, for instance, allow the plant owner to produce and/or store heat, utilizing renewable and fluctuating electricity resources when available, thus balancing the power system. It also increases the capacity of the system, allowing the size of the thermal storage to be reduced.

7.4 Heat production optimization

To understand the fundamental drivers of heat production economy, it is important to look at the distinction between base-load and peak-load heat demand. 'Baseload' is, as the term implies, the part of the load that is constant during the largest part of the year. This demand is usually meet by EfW plants, CHP, or alternatively by geothermal heat production due to low marginal cost. These units are also categorized as high priority production units.

When the baseload unit becomes outregulated due to high demand, smaller balancing units are switched on (fast regulating) to match peak demand. These smaller units are categorized as low priority production units and are typically oil- or gas-fired heat-only boilers that have a relatively high marginal/operational cost.

Implementing a thermal storage into a DHC network enables the operator to store baseload heat at times when heat demand is low. The accumulated heat can then be used to smooth out production peaks during high demand periods. Supplying heat from the storage (low cost baseload heat) in periods of peak load allows the network operator to avoid turning on the more costly peak load plants.

By utilizing heat storage in a DHC system, the operator has the opportunity to fully exploit the possibilities of an extraction CHP, as the storage can be used as a short-term reserve. This model does, however, have its limitations, because the scheduled operation of the store takes priority, meaning that it cannot serve as an emergency reserve at the same time. The network operator must choose to work the storage either as a peak reserve or as a reserve to optimize electricity production in the extraction plant. It should be noted that integrating a heat store in a DHC system does not add capacity to the system and should not replace back-up or peak boiler capacity. It is merely a mean to allocate production units in the most economically optimized way.

During periods with peak demand, where the available high priority capacity (base-load capacity) is exceeded, a fully discharged storage should remain discharged until low-cost production capacity becomes available. This is something that must be considered in the control algorithm of the storage unit.

Another reason for installing storage capacity in relation to peak production is that many heat-only boilers operate at a fixed or, in some cases, minimum output, which seldom corresponds to the actual demand in a peak load situation. The operator is then forced to downregulate the baseload units to balance the mismatch. This implies that more heat than necessary is supplied from low priority units, which drives up the operational cost to an unnecessarily high level. Thermal storage can be the solution to this type of problem, as it can be designed to absorb the variations in peak load.

When operating a CHP in a smaller and less complex heating network, thermal storage allows the operator to shut down the production unit entirely when electricity prices are low or if he wants to avoid delivery/handling of fuel at certain times, e.g., at the weekends.

The amount of low priority capacity that can be replaced by high priority capacity, hence sizing of the storage, depends to a high degree on the annual and daily variations in the individual network (Figure 7.3).

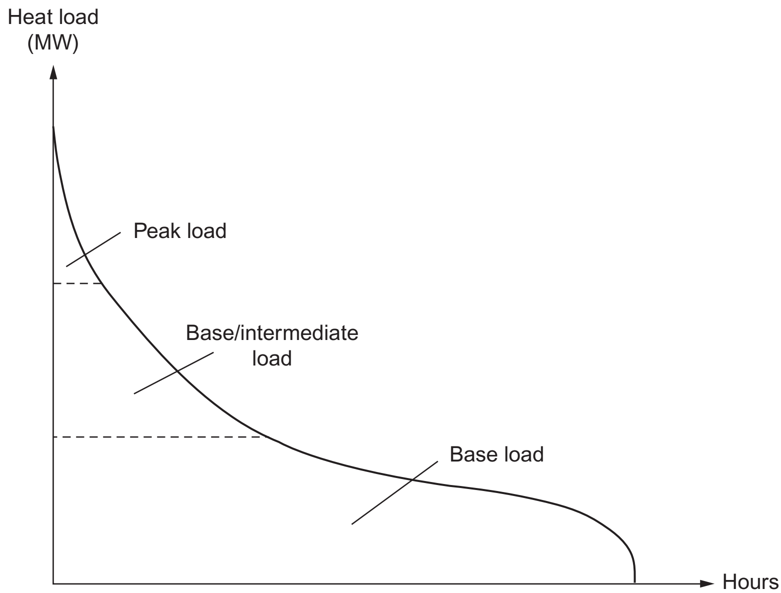

Figure 7.3 Duration curve representing heat demand on an hourly basis in arbitrary district heating network.

7.5 Design parameters and operational principles

Designing a thermal store requires careful consideration with regard to the operational characteristics (e.g., load profile), flow, and return temperatures and pressure levels of the network in which the storage is intended to function.

7.5.1 Constant water content (mass basis)

One of the main characteristics of a water-based thermal store is the constant water mass principle. This implies that the volume of water changes, depending on the energy content (temperatures) in the tank, but the mass of water remains constant, i.e., if a specific amount of hot water flows into the tank (charging), the same amount is displaced from the tank simultaneously.

7.5.2 Pressure levels

If storage is intended to be connected in a low temperature network (forward temperature well below boiling point), a pressure-less tank is preferred. In practice, the pressure-less tank is actually slightly pressurized, as a minor overpressure is maintained in the top of the tank. To prevent oxygen from penetrating the water surface inside the tank, a steam- or nitrogen-blanket is used.

If the storage is used in connection with a larger system, e.g., in a DH transmission system temperatures well above waters atmospheric boiling point may occur. Typically, temperatures up to 120 °C are used in this type of system and, using a none-pressurized store would result in constant boiling in the top the tank. This is not desirable, and instead, a pressurized storage should be utilized.

7.6 Operational schemes (control regimes)

In this section, different operating concepts used for controlling the thermal storage are introduced. The control strategy, as well as the way in which the store is integrated into the network, depends on a number of things, e.g., operating temperatures, pressure level, and the practical circumstances regarding the physical installation. The store can be connected to the network either directly or in a pressure-separated configuration.

7.6.1 Directly connected to the network

When a storage unit is connected directly to the network, it may be designed so that it functions as a pressurization vessel. Changing temperatures in the network will have the unfortunate consequence that the water inside the system expands and contracts, causing the volume to change continuously. For this reason, water must be drained from or supplied to the system to compensate.

In a network with no thermal store installed, the network pressure is maintained by installing a similar vessel where a prepressurized gas pocket absorbs the volumetric variations. When the network pressure increases, e.g., due to a drastic decrease in demand, water is drained from the network into this pressure vessel. In the opposite case, where the network pressure decreases, water may be supplied from the vessel into the network.

A pressure vessel or thermal store in direct hydraulic connection with the network will fulfil this function automatically and without any further control mechanisms, making this solution both simple and cost-effective.

The concept of direct hydraulic integration is illustrated by the simple model in Figure 7.4. Heat is supplied to the customer via the network pump, which is regulated so that adequate differential pressure is maintained throughout the entire DH network. The production pump circulates water from the return line through the CHP plant to the supply line. The production pump is regulated to match the current heat production at any given time by maintaining a constant supply temperature to the network.

A direct connection is preferred for the reasons explained above. The pressure potential of a given vessel is then determined by the level of the water surface in the tank relative to the reference level of the system in which it is connected. Strategic placement of the tank in an elevated position could be useful.

While the pressure-less tank may be sufficient in a smaller network, where the pipes are laid out in an area with relatively little height variation, it may prove inadequate in larger systems where physical circumstances prescribe higher static pressure.

Designing a thermal storage unit so that it serves both purposes implies taking into consideration the extra volume required to handle the expansion of the water in the network, as well as the volume change caused by water replacement during charging (hot water replacing cold water).

As discussed above, no external control measures are necessary for the direct connected heat storage (or pressurization vessel) to function. Charging and discharging of the storage unit is controlled autonomously utilizing the specific differential pressure between the supply and return line of the network. The pressure differential

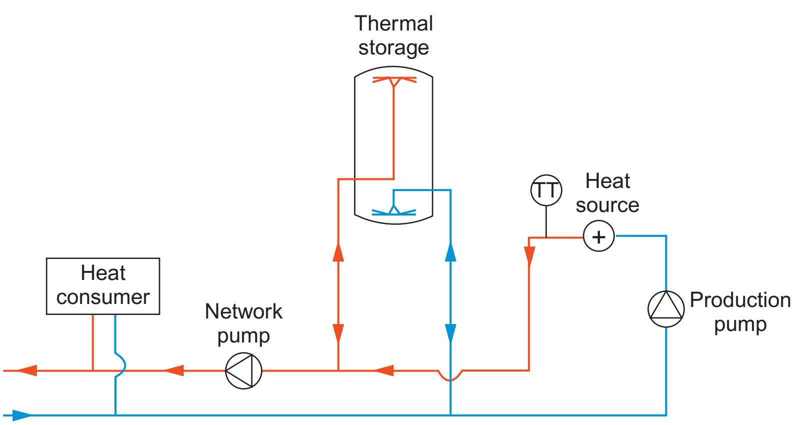

Figure 7.4 Thermal store *directly connected* to a heat network.

across the return and flow line of the system is generated by the network pump and the production pump.

Running the production unit at full capacity with a lower heat demand creates a positive differential pressure between the hot manifold (connected to the supply line before the network pump) and the cold manifold (connected to the return line before the production pump). The positive pressure difference will cause hot water to flow into the tank, while at the same time displacing the same amount of cold water to the return line, thus charging the heat storage.

In a case where the heat demand exceeds the capacity of the production unit, a negative pressure difference will occur between the supply and the return (assuming constant supply temperature is maintained). This will cause a flow through the store where cold water from the return is entering into the bottom of the store causing a discharge of hot water from the top of the store to the supply.

It is important to note that the number of heat storage in direct hydraulic connection is limited to a single store per network. This is due to the fact that pressure levels at different connection points can lead to water being accumulated in one tank, while content drops in another.

7.6.2 Pressure separated from the network

As an alternative to the direct connection concept described above, a thermal storage unit may be connected to the network decoupled from the static pressure, as outlined in Figure 7.5. In this system, a dedicated pressure vessel is required to allow for volumetric expansions/contractions. This design is more commonly used in larger systems with a higher degree of level variation. The connection points of the pressure-separated storage are identical to those in the direct connection model. The only difference is that the flow in and out of the tank is controlled actively by utilizing a pump and valve configuration (see Figure 7.5).

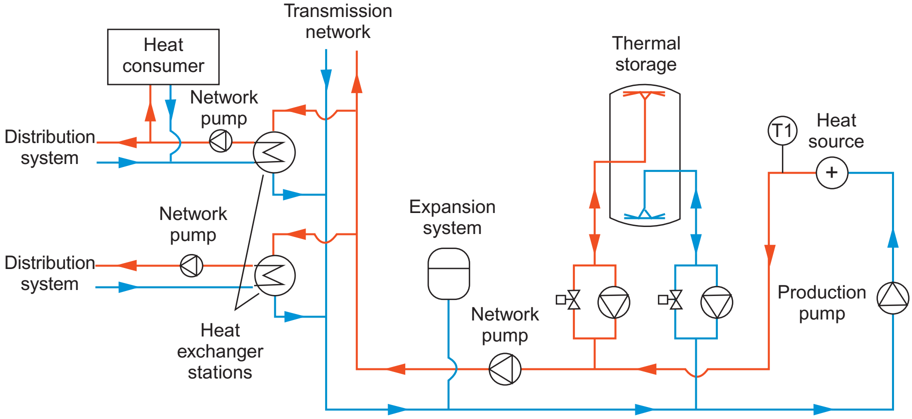

Figure 7.5 Thermal store with *pressure separation* from the heat network.

The water content in the tank should be maintained constant at all times (on a mass basis). This can be accomplished by controlling either pump in correspondence to the desired heat rate in or out of the storage (charging/discharging), while the other pump is governed by a mirror function, where the flow rate is temperature compensated according to the primary pump, thus balancing the amount of water in the storage tank.

Pressure-separated storage is a more technically complex solution and more costly to implement compared with a storage unit directly connected in the network. However, it may be the only option in coping with issues, such as large level differences in the pipe layout. One solution to overcoming level variations in a DHC network is to set the static pressure level in the network (pre-pressurization). Normally, these systems are 16 or 25 bar systems, which implies that specially designed tanks are required. This will drive up the investment cost, making pressure separated storage a more viable option, at least from an economic point of view.

Pressure separation can also be done by installing heat exchangers, making the storage unit part of a closed circuit. There is, however, a downside to using heat exchangers, as it incurs a heat loss, which in turn reduces storage capacity and complicates operation due to the temperature mismatch between the storage unit and the network.

Several pressure separated storage units may be installed in the same network, as they are hydraulically decoupled from one another. This implies that there is no risk of one tank *stealing* water from another.

7.7 Charging and discharging of directly connected TES

In this section, a brief illustrative summary is given on the processes of charging and discharging of a TES connected directly to the network.

7.7.1 Charging

Figure 7.6 gives a schematic outline of the most important factors and mechanisms affecting the charging scenario of the (hydraulically) directly connected TES.

Water is pumped from the return to the heat source using the production pump. The flow rate through heat source is governed by a preset supply temperature and controlled by a temperature transmitter (TT), which measures the output temperature after heat source.

The network pump delivers the required heat to the network by ensuring a suitable minimum difference pressure in all points of the network. By utilizing the differential pressure between the supply from the heat source and the return, any excess heat is diverted into the storage unit where cold water is displaced back into the return in the network.

7.7.2 Discharging

Figure 7.7 gives a schematic outline of the most important factors and mechanisms pertaining to the discharging scenario of the directly (hydraulically) connected TES.

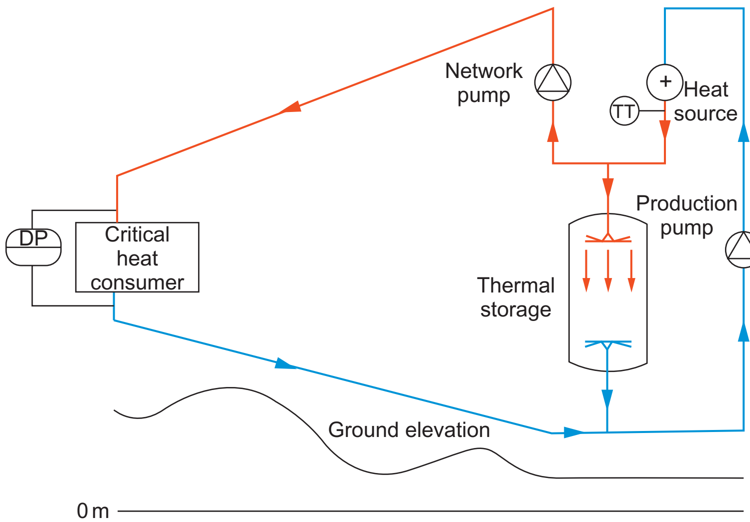

Figure 7.6 Principles of pressurization using thermal store—charging.

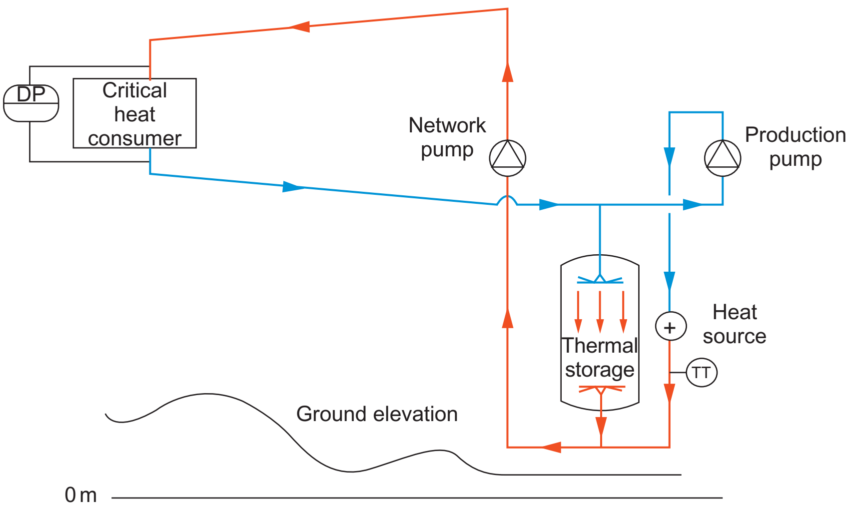

Figure 7.7 Principles of pressurization using thermal store—discharging.

If the demand in a network exceeds the available production capacity, heat can be drawn from the storage unit to assist in meeting the heat demand.

The supply pump (SP1) is governed only by the criterion of delivering minimum pressure difference in the critical point of the network. This implies that the suction pressure is lowered at the hot manifold of the store, which creates a negative pressure differential between the supply and the return.

In much the same way that the storage unit was charged based on the positive differential pressure, discharging happens when there is a negative differential pressure between supply and return in the network.

The conditions explained above apply to charging and discharging of the directly connected thermal store. However, when it comes to controlling charging and discharging sequences of a pressurized tank installation, active governance must be implemented, i.e., a pump and valve configuration controlled by an external algorithm as those briefly outlined earlier in this chapter.

7.8 Charging and discharging of a pressure separated TES

In this section, the reader will be familiarized with the simple control scheme and the specific control algorithms used for charging and discharging of a pressure separated TES, depending on the purpose of the storage tank.

There are two crucial paradigms connected to charging and discharging of pressure separated thermal storage:

- Mass flow control,
- Capacity control.

7.8.1 Mass flow control

Controlling the mass flow through the storage tank is essential because the water content in the tank remains constant (on a mass basis). The general principle of mass regulation is illustrated in Figure 7.8.

How much water is flowing through the tank depends on a number of issues. In most cases, the flow is determined by the network operator in terms of required capacity (MW),

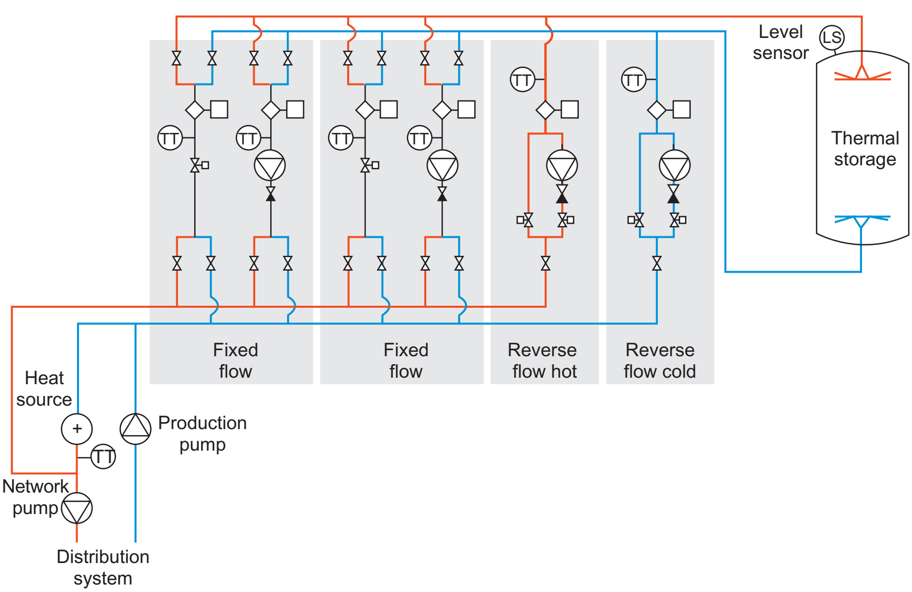

Figure 7.8 Mass flow control.

however, specifying the exact flow is, in most cases, very complex and depends on both long-term planning (24/48 h), as well as the hourly fluctuations in customer demand.

If the storage unit is situated in a remote location, flow may be controlled to obtain certain operation modes, e.g., to maintain a specific minimum pressure differential at a particular customer in the network. This can, for example, be the case with very large or demanding industrial customers.

When the pressure differential in the network gradually increases during operation, the operator knows that there is a surplus from the heat production and that he should start increasing the charge flow to the storage unit. Conversely, if the pressure differential in the network is decreasing during operation, it tells the operator that the heat demand is not met by current supply capacity and that he must increase the discharge flow in order to cover the heat deficit.

7.8.2 Capacity control

Instead of regulating the pumps in the charging/discharging loop according to the mass balance in the thermal storage unit, the water level in the expansion system (pressurization vessel) could be the governing factor. An increase of the water level in the pressurization vessel would indicate that too much water is being pumped into the network. This change in water level should then be used to signal an automatic controller to decrease the flow out of the storage tank, as well as to start increasing the speed of the inflow pump(s).

The general principle of capacity control is illustrated in Figure 7.9. Utilizing the capacity control scheme implies that the heat storage is acting as a part of the

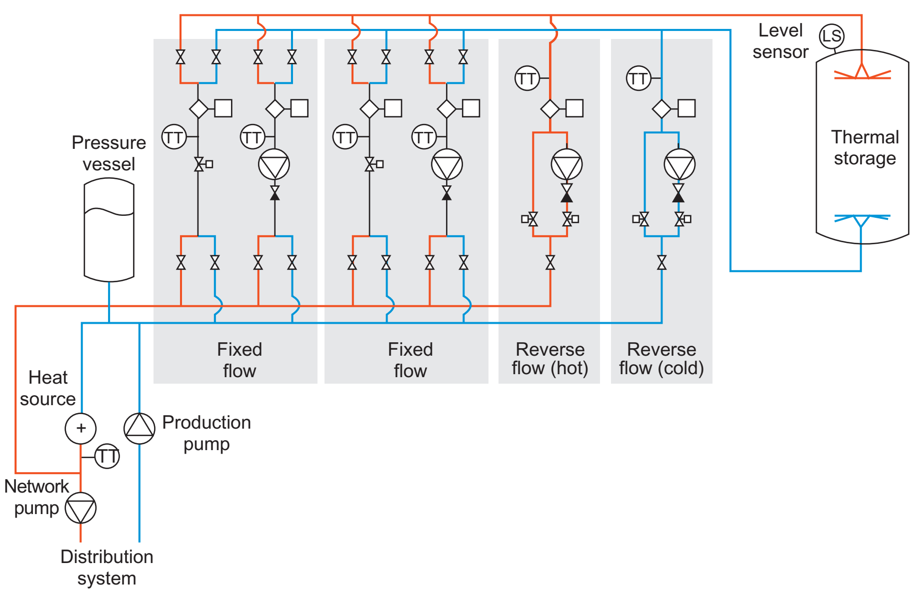

Figure 7.9 Capacity control.

pressurization system. In practice, the dedicated pressure vessel should still be able to function as an emergency valve in case a situation occurs where inappropriately high water levels are reached and water must be drained from the network.

7.9 Designing a thermal store

As mentioned earlier in the chapter, thermal stores can take various forms and shapes utilizing different designs and storage material. The common denominator of all storage types is that mass matters in the sense that different materials has unique properties, specific heat capacity being one of the most important ones.

The definition of *heat energy* is given from the following expression:

- $Q = m * C_p * \Delta T$,
- Q is the *quantum of energy* (J),
- m is the *mass* of storage material (kg),
- C_p is the *specific heat capacity* of the storage material (J/kg K),
- ΔT is the temperature difference between storage material and ambient temperature (K).

Looking at the individual components of the equation above, one can conclude that choosing materials with good heat properties allows for smaller storage units and vice versa at a given temperature level.

Furthermore, it is important to be mindful in choosing a storage material that can be handled easily and without any implications involved for the people handling it. Nor should the chosen material have any short- or long-term damaging effects to the environment, either local and global. Here, some of the more practical aspects of designing a thermal store will be elaborated upon.

7.9.1 Temperature

Often, the supply temperature in a thermal store is determined by factors such as:

- Customer segment,
- Network complexity,
- Variations in demand (demand profile).

Storage tanks can be divided into two categories, depending on the temperature set applying to the respective network into which it should be connected.

A storage tank connected to a network with a supply temperature below 100 °C is usually designed as a *non-pressurized tank*, whereas tanks utilized in high temperature networks (above 100 °C) are designed as *pressurized units*.

However, there are exceptions to the 100 °C-rule of thumb, e.g., if the operation of a given storage unit is limited to a relatively low number of hours each year. In cases where low utilization factors apply, a nonpressurized unit can be the more viable option in an above 100 °C network due to lower investment cost. Implementing a nonpressurized unit in a high temperature network also means that preventive measures should be taken in terms of temperature separation, i.e., either installing a by-pass around the store or shunting the inlet so that the supply water is below 100 °C before entering the storage unit.

There is a limit to the allowable span between supply and return temperature due to thermal tensioning in the tank. The tank should be designed to cope with the largest span possible. A suitable temperature difference in a nonpressurized vessel is approximately 30–40 °C. In a pressurized unit, temperature spans can be as high as 50–55 °C.

The lower temperature in the tank is predetermined from the return temperature in the network. The highest temperature allowed in the storage tank is limited to that of the energy source or whether a pressurized tank has been chosen or not.

7.9.2 Pressure

The static pressure affecting a given network is just as important as temperature in determining how to design a thermal store that suits the respective operating conditions. One should acknowledge the direct relation between network static pressure in the connection point and the height of the tank (height of water surface in the tank).

The height of the storage tank is restricted by certain physical constraints, which in turn limits the static pressure potential in the connection point. This may present some hurdles in designing the optimal tank, and one should consider this carefully when implementing pressure-less storage tanks in systems where static pressure is high.

Traditionally, nonpressurized tanks are suitable in systems where the static pressure does not exceed 6–7 bar or should the temperature become higher than 100 °C (risk of boiling).

7.9.3 Sizing

The tank size is determined based on a number of parameters of which some are more reliable than others. Ultimately, it comes down to economical assessment (a feasibility study) where some of following factors must be forecast:

- Electricity market price, to assess the share of excess production available for storage.
- Future heat prices, to assess the gain of having storage capacity in the system.
- Future supply/demand profiles, including network extensions and added heat production units.

A more predictable parameter used in the economical assessment and design of the thermal store is the capital cost of the storage unit in relation to the storage size.

The energy content of a storage tank is calculated using the temperature difference between the supply and return temperatures of the network, as well as the tank volume, where the height is the distance between the hot and the cold diffuser (remember to subtract the height of the transition zone, which is usually around 1 m thick).

The height to diameter ratio of the tank is a crucial design parameter, as this dictates the volume in relation to the surface area (heat loss). On the other hand, it is important that the designer also accounts for the volume of the transition zone, which is optimized (minimized) by increasing the height of the tank making it tall and slim. The optimal design lies somewhere in between these two parameters.

It has been best practice in the industry for many years to go with a height/diameter ratio above 1.5, trying to achieve a minimum of inactive tank volume (transition zone).

7.9.4 General design requirements (Europe)

In Europe, there is a distinction in the design criteria when designing hot water storage. If the storage unit is nonpressurized, it should be designed according to the standard EN14015. When designing pressurized tanks, the Pressure Equipment Directive (PED) applies.

Calculating the thickness of the tank shell (including roof and bottom plating), the designer should always include a minimum of 1 mm for corrosion allowance. Furthermore, it should be proven that the tank can withstand the transition zone passing any level in the tank twice a day, all year round for its entire technical lifetime (~45 years), without succumbing to failure due to fatigue.

7.10 Seasonal thermal storage

The primary focus of this chapter has been on short-term storage used in DHC networks. However, over the recent decade, we have seen long-term thermal storage catapulted up to the status of "proven technology," due to improved technology, and several more long-term seasonal storage units will be introduced over the next couple of years throughout Europe.

"Seasonal storage" is a broad term used to describe various technologies with different utilization potential. A seasonal store is per definition a store that can be charged during the summer, for instance in connection with solar thermal production, and retain the energy for later use during the colder winter months.

As mentioned earlier, various types of seasonal storage are available at present, e.g., boreholes, aquifer, or pit storage.

Borehole and aquifer storage, called BTES and ATES, respectively, are not particularly well suited for storing high temperature water, as it is the soil that is utilized as insulation capacity. Also, groundwater penetration can be an issue with this type of storage. These two types of thermal storage are more common in connection with combined heat pumps (winter) and refrigeration machines (summer), where heat can be collected or removed from buildings and stored in the ground during warm periods and reutilized via heat pumps during winter time. BTES or ATES can be used in district cooling systems because low temperature water is utilized.

Pit storage (also known as "pond" or "pool" storage) is better suited and more widespread within the DH industry. Here, high temperature water can be stored, effectively isolated from the soil or groundwater, in reservoirs with a volumetric capacity of up to 100,000 m^3. Pit storages are often utilized in connection with large scale solar thermal production.

From experience, it has been shown that it is possible to store hot water (up to 95 °C) for several months with very small losses incurred (as low 1 °C per month).

7.10.1 Phase change material

Heat storage is needed to even out the divergences and to increase the performance of the heating system. The most common solution by far is to install a well-insulated water tank in the heating system. This solution is preferred due to the very favorable heat capacity properties that water possesses. Less developed alternatives are under investigation, including heat storage in phase change material (PCM), such as sodium acetate, where large quantities of energy can be stored as latent heat in PCM, with the possibility of stable super-cooling and partly loss-free thermal storage. The concept of super-cooling is shown in Figure 7.10.

The reason why this area has not been investigated intensively is that most types of PCM can exhibit unstable behavior in the supercooling process. However, recent studies have shown promising results regarding the opportunities of combining solar heating and seasonal heat storage in PCM with stable supercooling (Sharma, 2007; Pramod, 2011).

One of the great advantages of PCM compared with water as a storage medium is the higher heat storage density (kJ/kg) due to the latent heat storage potential in PCM. This means that for any given storage capacity, the physical storage volume needed is somewhat smaller if PCM is used compared with water. However, PCM is not in itself a great heat conductor material (also it does not flow well in solid form); therefore,

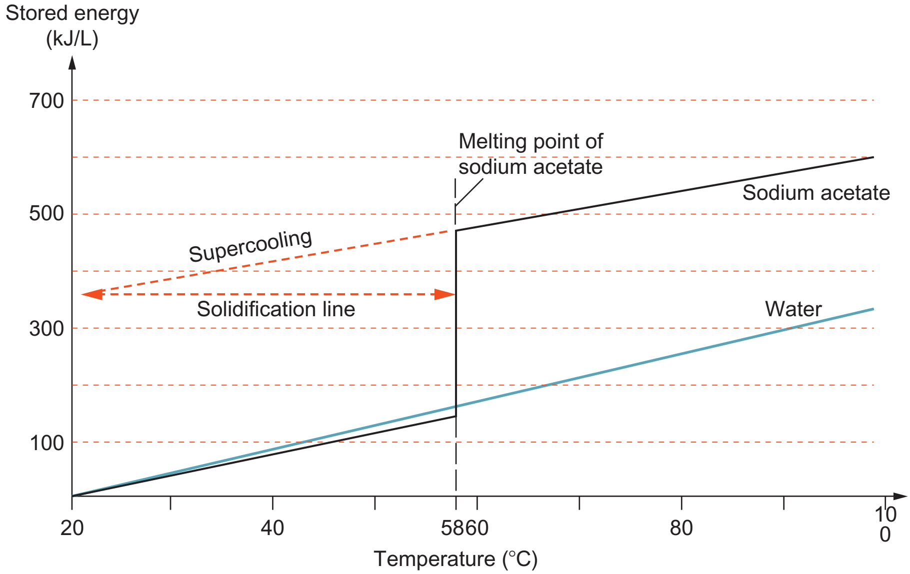

Figure 7.10 Supercooling of phase change material (PCM).

heat exchangers must be used to transport the heat into either a tank or directly into a space heating loop. For this purpose, water is utilized.

PCM in the heating system can have different purposes depending on how it is integrated. In the above-mentioned system, the PCM is used as an independent heat store separate from the rest of the solar heating system. An experimental study by Mazman et al. (2008) has pointed out another advantageous applications of PCM in hot water storage. Experiments were carried out where four PCM (PCM in aluminum containers) modules were integrated directly in the top of a solar domestic hot water (DHW) tank (the hottest part of the tank). The primary purpose of this was to increase the heat storage density of the hot water tank. The studies concluded that cooling of the water (heat loss) was postponed noticeably compared with an identical tank without the PCM modules, hence increasing the performance of the system.

Case studies

Kings yard and Stratford City (Olympic Park), UK

- Commissioned: 2009,
- Number of end-users: –,
- Type of storage: above ground tank storage (short-term storage).

Kings Yard and Stratford City Energy Centres provide DHC to the Olympic Park and Stratford City developments.

The system includes two cylindrical above-ground storage units, with the following specifications:

- $1 \times 800\,m^3$ hot water storage, up to 100 °C (diameter/height—7.5 m/18 m),
- $1 \times 800\,m^3$ cold water storage, down to 4 °C (diameter/height—7.5 m/18 m).

Marstal—Sunstore 4, Denmark

- Commissioned: 2012 (part of the world's largest solar thermal plant),
- Number of end-users: 1550 substations,
- Type of storage: pit storage (seasonal storage).

The overall scope of the Marstal—Sunstore 4 concept is to demonstrate a 100% renewable energy to supply a DH system that is cost-effective and innovative.

The system comprises of a 75,000 m^3 pit storage connected to 15,000 m^2 flat plate solar collectors, a 4 MW wood chip-fired CHP with ORC, and a 1.5 MW CO_2 heat pump.

Sunstore 4 is connected to the Sunstore 2 plant, which has more than 18,000 m^2 of solar collectors and a 10,340 m^3 pit storage (see: http://www.sunstore.dk/SUNSTORE%20.html).

Drake landing, Canada

- Commissioned in 2007 (first seasonal storage in North America),
- Number of end-users: 52 low energy housings,
- Type of storage: above ground horizontal tank storage (short-term storage) + borehole thermal storage (long-term storage).

The scope of the concept is to showcase energy efficient energy supply in a small community consisting of 52 single family homes. After 4 years of successful operation, a solar fraction of 90% was achieved due to a very flexible (district) heating system, in which both long- and short-term storage played a pivotal role.

The Drake landing concept comprises of 2300 m^2 single-glazed solar thermal collectors, a 1.6 MW CHP, a borehole storage and two cylindrical storage tanks (horizontal) (see: http://www.dlsc.ca/).

Dronninglund, Denmark

- Commissioned: 2014,
- Number of end-users: 1350 substations,
- Type of storage: pit storage (seasonal storage).

The aim is to cover more than 50% of the consumer's yearly heat demand.

The system was built to lower heating bills and to secure the heat price over the next 25 years in the small community of Dronninglund. The system comprises of a 62,000 m^3 pit storage connected to 37,275 m^2 flat plate solar collectors (see: http://www.dronninglundfjernvarme.dk/firmaprofil/solvarme).

References

Mazman, M., et al., 2008. Utilization of phase change materials in solar domestic hot water systems. http://www.sciencedirect.com/science/article/pii/S0960148108003704.

Pramod, B., 2011. http://www.sciencedirect.com/science/article/pii/S1364032112003711.

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Sources of further information and advice

For more literature and general knowledge on DHC and TES, go to

http://www.etank.com/—Design Software ETANK2000 for above ground storage tank design.

http://www.euroheat.org/—International association representing the District Heating and Cooling (DHC) and Combined Heat and Power (CHP).

http://www.heatroadmap.eu/—A low-carbon heating and cooling strategy for Europe.

http://www.ramboll.com/services/energy/district-energy.

http://www.4dh.dk/—Low temperature district heating.

Further Reading

CEN, 2004. EN14015:2004. Specification for the design and manufacture of site built, vertical, cylindrical, flat-bottomed, above ground, welded, steel tanks for the storage of liquids at ambient temperature and above. http://www.techstreet.com/products/1207174.

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Fan, J. et al., 2011. Heat transfer capacity of a heat exchanger module for seasonal heat storage. In: ISES Solar World Congress 2011, Kassel, Germany.

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