Thermal energy storage systems for district heating and cooling

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18.1 Introduction

The context for this chapter is the current use and typical applications of thermal energy storages within contemporary district heating and cooling systems. Storage examples and experiences are mostly provided from the Nordic countries in Europe. No focus is directed towards new storage methods or technical development of the current storage technologies used.

Section 18.2 presents an overview of the overall district heating and cooling and provides the and context with its basic fundamental idea. Section 18.3 presents current thermal energy storage applications within district heating and cooling systems. The eight issues discussed are cash flows from storages, a new variation assessment method, distributed heat storages, hourly heat storage in networks, daily heat storages with an analysis of relative heat storages in 209 district heating systems, weekly heat storages, seasonal heat storages, and daily cold storages with an analysis of relative cold storages in nine district cooling systems. Two expected major future trends for thermal energy storages are then discussed in Section 18.4. Major information sources concerning thermal energy storages in district heating and cooling systems are commented on in the final section.

18.2 District heating and cooling overview

The fundamental idea of district heating and cooling is currently to recover fuel and heat flows that are otherwise lost, both from heat sources inside and outside the energy system. The dominant factor here is the economy-of-scope from synergies by heat recycling. But economy-of-size also contributes to the fundamental idea, as large district heating and cooling systems contain major scale effects. Considerable growing interest in renewable heat supply also generates a demand for distribution of heat from biomass, geothermal, and solar energy in urban areas through district heating and cooling systems.

Traditional assessments of district heating and cooling systems are provided by Werner (2004) and Frederiksen and Werner (2013). Examples of recent assessments from countries that are considering expanding their current use of district heating and cooling are Rezaie and Rosen (2011) and Hawkey (2012).

District heating systems can be found in Europe, Russia, Korea, China, Japan,

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and North America. Almost no system exists in the southern hemisphere. High market shares, when connected buildings constitute around 50% of all national heat demand in buildings, can be found in Denmark, Finland, Sweden, Estonia, Latvia, Lithuania, Poland, and Russia. Globally, about 80,000 systems are in operation with 600,000 trench kilometres of district heating pipes. About 11 EJ heat are delivered annually worldwide to cover low temperature heat demand in industrial processes and to meet space heating and hot water demand in residential and service sector buildings. The corresponding European figures are about 6000 systems, 180,000 km of trench length and just above 2 EJ of heat delivered. Typical prices for district heat deliveries within the European Union were €11–22/GJ, with an average of €16/GJ in 2011. These prices are normally lower than or equal to those from local boilers using fossil fuels with different national energy taxes, such as carbon dioxide taxes. The price variation comes from the energy tax levels that vary from country to country. A European price exception is always the geothermal district heating systems in Iceland, which sold heat for only €3.1/GJ in 2011. More detailed statistical information about district heating and cooling in various European countries can be found in Euroheat and Power (2013).

District cooling systems appear in North America, the Middle East, Far East, and Europe. Annual cold deliveries have been estimated at 400 PJ in the Middle East, 90 PJ in the USA, 13 PJ in Japan, and 10 PJ in Europe. More than 100 district cooling systems can be found in Europe, mostly in France, Sweden, and Germany. Hence, the current use of district cooling is much lower than the use of district heating. Similar to district cooling is the hybrid solution of heat deliveries from district heating systems to customer absorption chillers. This variant, often called ‘warm district cooling’, appears in New York, Korea, Germany, and Sweden.

Seasonal and daily load variations give incentives for thermal energy storage in district heating and cooling systems. The seasonal load variation comes from the seasonal variation in outdoor temperature giving different space heat and cold demands throughout the year. The daily heat load variation comes from the social use patterns for hot water preparation and time clock operation of ventilation systems. High daytime outdoor temperatures during summertime generate demand for space cooling, mostly in service sector buildings. With thermal energy storages, the heat or cold generation can be moved to times when the cost for this generation is at to a lower variable cost. Deliveries can also be moved to times when the prices and revenues are higher.

18.3 Advances in applications of thermal energy storage systems

18.3.1 Typical cash flows from thermal storages

Various situations can be defined that generate cash flows from investments in storage installations. Examples of situations that generate new cash flows from these storage investments are described as follows.

- Combined heat and power (CHP) plants generate both electricity and heat. With heat storage, the stiff generation connection between heat and power generation can be made more flexible. Daytime market prices for electricity are normally higher than night-time prices. With heat storage, the plant operation at part loads can then be concentrated to day-times, giving higher electricity revenues to a CHP plant. The heat storage will then be charged during the day and discharged during the night.
- Frequent load changes in a biomass boiler can give somewhat lower seasonal conversion efficiency. With heat storage, the boiler load can be kept more constant, maintaining some higher boiler conversion efficiency. The heat storage will then be charged during the night, when the system loads are lower, and discharged during the day, when the system loads are higher.
- Recovery of industrial excess heat from various batch processes will be easier to implement if the strong variation in the heat recovery can be reduced with heat storage before heat supply to the distribution network. The heat storage will then be charged when the batch process is running and discharged when the industrial process does not generate excess heat.
- Heat or cold storage can reduce the demand for more expensive peak loads. The storage will then be charged during the night, when the system loads are lower, and discharged during the day, when the system loads are higher.
- Heat or cold storage can also reduce the demand for installed peak load capacity if the storage is used actively during system load peaks. The cost benefit is then the avoided investment cost in peak load capacity.
- Heat or cold storage tanks can also act as pressurization tanks. This static pressurization can either be accomplished by a pressurized storage tank or an atmospheric storage tank located at the highest system altitude. The cost benefit represents then the avoided alternative investment in a pressurisation system without the storage possibility.
- A water tank for heat or cold storage can also be utilized as water storage in case of a major water leakage in the distribution system.

The total annual cash flow will then be the product of the number of times that the situation appears during a year and the cash flow from each situation. Hence, it is easier to reach an acceptable profitability for a heat storage solving many daily load variations than for a heat storage solving a seasonal load variation, which provides only one cash flow each year. Thermal storage also becomes more profitable if during a year it can utilize many of the different cash flow situations listed above.

18.3.2 A new variation assessment method

In order to quantify the various load variations in a district heating system, a variation assessment method with two variables has been defined in Gadd and Werner (2013). The main purpose has been to provide a simple separation of the seasonal and daily heat load variations during a year.

The first variable in the assessment method is the annual relative seasonal variation, expressing the proportion of the annual heat supply that is supplied by daily average heat loads over the annual average heat load. The second variable is the annual relative daily variation, expressing the proportion of the annual heat supply that is supplied by hourly average heat loads over the daily average heat loads. This assessment method has been developed for understanding the load variations in district heating systems, but can be applied to any activity with activity load variations.

Some applications of this variation assessment method are presented in Figure 18.1. The separation of the seasonal and daily variations has been applied to one district cooling system (Helsingborg in 2009), one electricity system (Sweden in 2008), and 20 Swedish district heating systems.

The electricity system is characterized by both low seasonal and daily load variations. The district heating systems have about the same daily variation as the electricity system, but the seasonal variation is much higher. The district cooling system has about the same seasonal variation as the district heating systems, but the daily variation is higher. For the 20 Swedish district heating systems, the average annual relative daily variation was estimated to be 4.5%, according to Gadd and Werner (2013). The average annual relative seasonal variation was estimated to be 24%.

The two major conclusions from Figure 18.1 are:

- In district heating and cooling systems, seasonal variation is more dominant compared to the daily variation.
- In district cooling systems, higher incentives appear for reducing the daily load variations since these daily variations are more pronounced than the corresponding variations in district heating systems.

18.3.3 Distributed heat storages

Individual hot water use is associated with very high capacity demands compared to the amount of heat required during a year, since the individual hot water use is

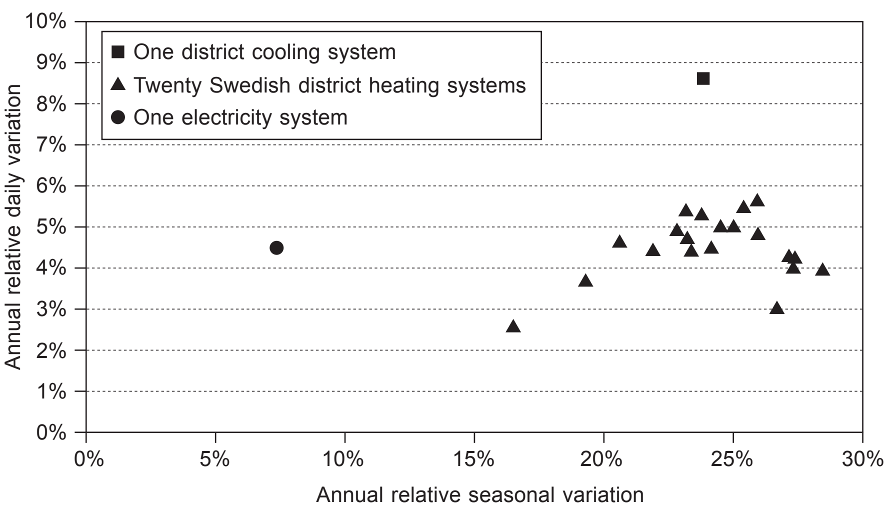

Figure 18.1 Typical compositions of annual relative seasonal and daily variations for three different energy supply systems.

concentrated to only about 100 hours per year. Therefore, hot water preparation is almost always associated with hot water storages when the heat is generated in individual boilers, either by fossil fuels, electricity, or heat pumps. The alternative of installing boilers with the necessary capacity for instantaneous preparation of hot water would be far too expensive.

District heating systems are normally so large that the requested aggregated hot water preparation capacity becomes very small because of high diversity in the system. The requested capacity in order to generate hot water for 1000 flats is only 1% of the sum of the individual capacity demands. Thus, short heat load peaks from individual hot water storages do not influence the total aggregated heat load at the heat supply units. An important insight is then that local heat storages in the customer substations are not needed in order to reduce the heat generation capacity in the district heating system. This conclusion is also valid for fully occupied hotels, where the hot water demands can be concentrated to the mornings, but the heat exchanger should be properly designed for these high demands. However, in some countries, local distributed hot water storages are installed in the substations in order to reduce the size of the pipes that connect the buildings with the district heating system.

18.3.4 Hourly heat storage in distribution networks

One common operation strategy in district heating systems is to increase the supply temperature shortly before expected peaks in the aggregated heat load. This kind of very short-term storage operation strategy has been defined and presented by Suttor (1968) and Glück (1983). Here, the distribution network itself can be used as an active heat storage. However, the timescale for this heat storage is very short, since the water turnover in a district heating system is around 1–2 hours depending on system size. The local storage effect will disappear when the new supply temperature reaches the flow control in each substation. Then the flow will be adjusted to consider the new supply temperature at the current heat load.

One example of an expected heat load peak is the use of showers during mornings. By increasing the supply temperature some degrees between 3a.m. and 6a.m., the network will be charged with more heat in advance. This charging will reduce the flow peaks later during the morning, representing the discharge. This temporary temperature increase should be limited in degrees in order to avoid low cycle fatigue of the steel pipes in the distribution networks.

In the same manner, the supply temperature can be reduced when lower heat loads are expected, representing a reduction of the heat content in the network. The charging will then appear when the supply temperature is increased when the lower heat loads will be effective.

18.3.5 Daily heat storages in district heating systems

Relative sizes of installed heat storages from 209 district heating systems located in the five Nordic countries are presented in Figure 18.2. The total heat supply into these

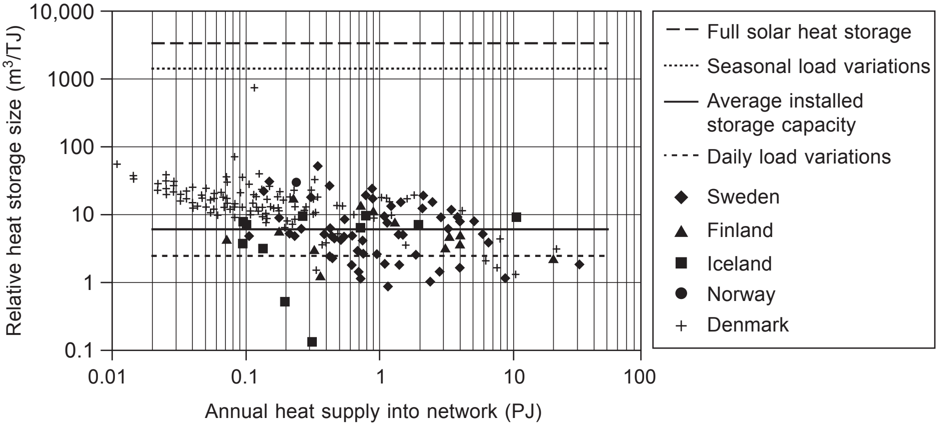

Figure 18.2 Relative heat storage sizes with respect to annual heat supply into networks in 209 Nordic district heating systems.

systems amounts to 261 PJ/year and the total installed water volume in these heat storages is currently 1.6 million cubic metres. The information about installed heat storage sizes has been collected from four different information sources (Nordvärme, 1993; Lindberg and Breitholtz, 1998; Rodoverken, 2013; and Hofmeister, 2013). The relative storage sizes estimated show a wide variation from 1 to 40 m^3 per TJ of heat supplied, with a weighted average of 6 m^3/TJ. This wide variation reveals that the design aims for the heat storages installed varies considerably among the systems studied.

Three reference levels are included in the figure. The highest reference level is the heat storage needed to fully use solar energy in a district heating system. This level has been extrapolated from real operational data from the Marstal system in Denmark, giving the demand to store 56% of the annual heat supply with an installed storage capacity of 3330 m^3/TJ, if solar heat should cover the whole annual heat supply. The remaining 44% of the heat supply can then be directly delivered from the solar collectors without heat storage. The second reference level represents the demand to counteract the whole seasonal load variation. The heat supply plant can then run on a constant load throughout the whole year. On average, 24% of the annual heat supply was supplied over the annual average heat load in 20 Swedish district heating systems, according to Gadd and Werner (2013), giving the required installed storage level of 1430 m^3/TJ. The third reference level represents the demand to counteract all daily load variations, giving the required installed storage level of 2.5 m^3/TJ, according to Gadd and Werner (2013).

The conclusion from Figure 18.2 is then that almost all the installed heat storages are used to manage daily heat load variations, since most of them are somewhat larger than the level of 2.5 m^3/TJ. Hence, the most typical application of heat storages in district heating systems is for short-term purposes. Only one system in Figure 18.2 is near to managing seasonal load variations. This is the Marstal system in Denmark, which will be discussed further in Section 18.3.7.

The most common heat storage technology for managing daily load variations is large water tanks. The largest installation found in our heat storage inventory was the 96,000 m^3 heat storage in conjunction with the Reykjavik district heating system in Iceland. The heat storage is used in order to eliminate the heat load variations when supplying geothermal water to the district heating system. A description of the use of the heat storage in the district heating system can be found in Gunnlaugsson *et al*. (2000).

Other technologies than water tanks for heat storage in district heating systems are very rare. One example is the 15,000 m^3 rock cavern heat storage in Avesta, Sweden. It was originally built in 1982 for research purposes (Rehbinder, 1985), but it is still in use in conjunction with the Avesta district heating system.

18.3.6 Weekly heat storages in district heating systems

One application of weekly heat storage use is the operation of a biomass boiler during the summer season, when the heat loads are low. A biomass boiler can normally only generate heat above a certain minimum boiler capacity, which can be higher than the typical summer load. This situation is solved by keeping the boiler in operation at a higher capacity during some days in a week, while meeting the system load and charging the heat storage at the same time. The boiler is then closed during the rest of the week, while the low system load is met by discharging the heat storage.

18.3.7 Seasonal heat storages in district heating systems

Seasonal heat storages are currently not normally used in district heating systems, since the required large heat storages would be too expensive compared to the current economic benefit of the storages. However, some research focus has been directed towards major heat storages for many years to capture solar energy during the summer for later delivery during autumn and winter. An early research demonstration example was introduced in 1982, when the Lyckebo rock cavern, with a 100,000 m^3 capacity, was built in Sweden. The solar energy supply was initially simulated by use of electric boilers from the national surplus of nuclear power during the summers.

The Marstal district heating company installed one major pit heat storage of 10,000 m^3 in 2004 in conjunction with a European research project called Sunstore 2. The purpose was to learn the storage technology for seasonal storage of heat gained from large solar collector fields. In 2012, the heat storage capacity was extended from 10,000 m^3 to 85,000 m^3 with a new 75,000 m^3 pit heat storage, mainly financed through a FP7 project called Sunstore 4. This gave considerable high relative heat storage of 740 m^3/TJ, which is near to full seasonal heat storage according to Figure 18.2. Thus, the Marstal district heating system became the first system in northern Europe to reach this favourable position. A presentation of this recent extension of heat storage capacity in the Marstal district heating system is provided by Pauschinger and Schmidt (2013).

18.3.8 Daily cold storages in district cooling systems

The high daily variation in cold loads during warm summer days gives a high incentive for cold storages in district cooling systems, through which the total installed capacity of chillers can be substantially reduced. The cold storage will then reduce the investment cost and the operating cost for chillers installed for the total peak capacity.

Installed cold storages in district cooling systems show a much higher diversity with respect to various storage technologies used compared to the dominating water tanks for heat storages. Ice storages are used in Chicago (District Energy Editorial, 2012), Paris (Schmid, 2007), and Yokohama (MM21DHC, 2013). Rock caverns are used in Helsinki (two cold storages with volumes of 11,500 m^3 and 23,500 m^3) and in Stockholm (the Hornsberg cavern with a volume of 50,000 m^3). A groundwater aquifer cold storage is used in Sollentuna, Sweden with an active water volume of 160,000 m^3. But at smaller water volumes, ordinary water tanks are used. One example from Halmstad, Sweden, with a 2000 m^3 water tank is shown in Figure 18.3.

Relative sizes of installed cold storages from nine district cooling systems located in Sweden (Stockholm, Norrenergi, Västerås, Sollentuna, Uppsala, Halmstad, and Helsingborg), Finland (Helsinki), and France (Paris) are presented in Figure 18.4.

Figure 18.3 The district cooling plant in the Halmstad University campus area is owned and operated by Halmstad Energy and Environment. The plant contains 3.6 MW of absorption chillers, mainly fed by heat from waste incineration through the district heating systems. The cold water storage cylinder to the left has a storage capacity of 24 MWh. Photo: Sven Werner.

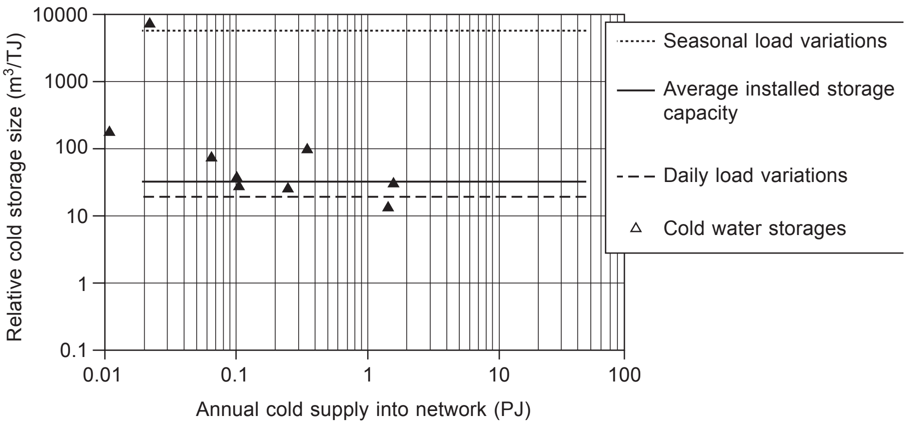

Figure 18.4 Relative cold storage sizes with respect to annual cold supply in seven Swedish district cooling systems, one Finnish system and one French system.

The total cold supply into these systems amounts to 3.9 PJ/year and the total installed water storage volume is 0.13 million cubic metres, excluding the large aquifer storage in Sollentuna. The relative storage sizes estimated show a wide variation from 10 to 100 m^3 per TJ of cold supplied, with a weighted average of 32 m^3/TJ. This wide variation reveals that the design aims for the cold storages installed also varies among the district cooling systems studied. The relative cold storage volumes are higher than the relative volumes for heat storages for two reasons: the active temperature difference is smaller (only 10–12°C) and the daily variation during peak conditions is higher in district cooling systems.

Two reference levels are included in the figure. The highest reference level represents the demand to counteract the whole seasonal load variation. According to Figure 18.1, 24% of the annual cold supply was supplied over the annual average cold load in the Helsingborg district cooling system, giving the installed storage level of 5700 m^3/TJ. The second reference level represents the demand to counteract all daily load variations, giving the required installed storage level of 19 m^3/TJ, according to the relative daily variation of 8.6% for the Helsingborg district cooling systems in Figure 18.1.

The conclusion from Figure 18.4 is then that almost all installed cold storages are used to manage daily cold load variations, since most of them are somewhat larger than the level of 19 m^3/TJ. Hence, the most typical application of cold storages in district cooling systems is for short-term purposes. Only one system in Figure 18.4 is designed to manage seasonal cold load variations. This is the Sollentuna system, which has a high relative cold storage volume of 7400 m^3/TJ. This seasonal cold storage is charged during the winter by using cold seawater from the Edsviken cove of the Baltic Sea as the cold source. The groundwater aquifer is cooled by using heat exchangers between the sea and groundwater.

18.4 Future trends

Two possible trends can be expected in the future with respect to thermal storages in district heating and cooling systems: seasonal heat storages and heat storage for balancing the power system.

18.4.1 Seasonal heat storage in district heating systems

The base load plants in the current district heating systems have rather low variable cost. The peak load plants are much more expensive to operate since they use fossil fuels, sometimes associated with high energy or carbon taxes. Thus, an incentive for future cash flows exists for reduced peak capacity and less use of expensive peak fuels. This storage demand can be fulfilled with large pit heat storages. Experience from the new large Marstal heat storage can be used to install much larger heat storages with several million cubic metres. With this future extrapolation of possible water volumes, the whole seasonal load variation can be eliminated in medium-sized district heating systems. This operational strategy is much more favourable and cost-effective than storing solar heat to the winter according to Figure 18.2, since a smaller relative storage volume is required. Thus, this kind of seasonal heat storage should prove more profitable.

18.4.2 Exchanging balancing power with electricity grids

Expectations of more renewable electricity generation in the electricity supply will give higher proportions of variable power generation from solar and wind energy in the future. District heating systems can then provide balancing power to the future electricity systems similar to the plans to use the gas supply system for the same purpose. This balancing power associated with district heating can be generated by a combination of CHP plants, large electric boilers, and large heat pumps. The CHP plants can supply electricity during generation shortages. The electric boilers and heat pumps can consume electricity during generation surpluses.

The future benefits from higher interaction between the European power system and the European district heating systems have been analysed by Connolly *et al.* (2013). A high interaction makes it possible to add a further 65 TWh/year of wind energy into the power system, since the associated wind power peaks can be absorbed in the district heating systems by electric boilers and heat pumps.

18.5 Sources of further information and advice

The use of thermal storages has a long tradition within district heating systems, since the daily load variations are modest, so these variations can be eliminated with rather small heat storages. However, this commercial use of heat storages has not always been properly documented in international scientific journals.

Early descriptions of heat storages within district heating systems can be found in Margolis (1930), Goepfert (1964), and Scholz (1988). More recent information sources are Ekono/FVB (2002) and Dittmann and Netske (2010). In general, the journal *Fernwärme International* (later renamed to *Euroheat & Power* in the 1990s) has been a good information source for all various aspects of district heating and cooling since 1972.

The current use of cold storages in district cooling systems and corresponding technology is presented in more detail in Vadrot and Delbes (1997), Dittman (2007), IDEA (2008), and Urbanek (2012).

Other information sources are the national district heating research programmes run by the Swedish and German district heating associations. The Swedish district heating research programme has provided almost 1000 research reports since 1975 and some of these reports are associated with thermal energy storage.

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