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Abbreviations

CES	Cold Energy Storage
CHP	Combined Heat & Power
COP	Coefficient of Performance
DC	District Cooling System
DH	District Heating
DHW	Domestic Hot Water
DS	Diurnal Storage
ESCo	Energy Service Company
HES	Heat Energy Storage
LCOH	Levelised Cost Of Heat
R	Return
S	Supply
SBH	Solar Block Heating
SDH	Solar District Heating
SH	Space Heating
ST	Solar Thermal
SS	Seasonal Storage

Abstract

Both district heating and solar collector systems have been known and implemented for many years. However, the combination of the two, with solar collectors supplying heat to the district heating network, is relatively new and no comprehensive review of scientific publications on this topic could be found. Thus, this paper summarises the literature available on solar district heating, and presents the state of the art and real experiences in this field. Given the lack of a generally accepted convention on the classification of solar district heating systems, this paper distinguishes centralized and decentralized solar district heating as well as block heating. For the different technologies, the paper describes commonly adopted control strategies, system configurations, types of installation and integration. Real-world examples are also given, to provide a more detailed insight into how solar thermal technology can be integrated with district heating. Solar thermal technology combined with thermally driven chillers to provide cooling for cooling networks is also included in this paper. In order for a technology to spread successfully, not only technical but also economic issues need to be tackled. Hence, the paper identifies and describes different types of ownership and financing schemes currently used in this field.

1. INTRODUCTION

District heating (DH) has been used as an efficient method to generate and distribute heat commercially for many years now. The world's oldest operational DH system is located in Chaudes-Aigues, France. It was put in operation in the 14th century, utilizing geothermally heated water. However, the first commercial system was developed in Lockport (USA) in 1877, utilizing steam as a heat carrier [1]. The first DH systems in Europe and Russia were installed during the 1920s and '30s, all with the aim of reducing the fuel demand and delivering heat more efficiently. This aim was further emphasized by including DH in the new national energy policies adopted by many countries during the oil crises in the '70s [2]. Nowadays, around 9% of the total heating needs in Europe are supplied by community and district heating systems [4].

On the other hand, the networks used to transport cooling are known as District Cooling systems (DC). The first known DC was installed in Denver, Colorado (USA) in 1889. Currently DC are well established in North America and the number of systems is increasing in Europe [3].

Similarly, solar energy has been harnessed to provide heat mainly for hot water and space heating for a long time. However, the combination of the two, using solar collectors to provide heat into a DH network is relatively new and has been demostrated sucessfully [5]. The first ST plants for DH date back to the late 1970s in Sweden. Since then, others plants have been installed mainly in Denmark, Germany, Austria and Sweden [6].

After a few decades of development and demonstration propelled by incentives [7], solar thermal has now become fully commercial without subsidies in Denmark [8]. Over the years, a number of scientific publications have dealt with this topic and, since 2009, the EU projects *SDHtake-off, SDHplus* and *SDHp2m* have promoted the spread of this technology, leading to a comprehensive set of guidelines and a website. In addition, there are and have been expert groups within the *International Energy Agency Solar Heating and Cooling Programme* dealing with this topic, e.g. *Task 45 (2011-14), Task 55 (2016-20).*

Heller [9] reviewed 15 years of R&D for central solar heating in Denmark. Likewise, in [10] a review of solar-assisted district heating plants in Germany is carried out and in [11] the project Solarthermie-2000 is reviewed. Additionally in [12,13] the penetration of solar district heating in Finland under different conditions is studied. Solar heating and cooling systems with borehole thermal energy storage was recently addressed and reviewed in [14]. Despite the scientific dissemination aforementioned, there is no comprehensive review of scientific publications dealing specifically with the integration of solar thermal energy in district networks. The last attempts to review solar thermal assisted district heating plants were made several years ago and the scope of all them is limited.

Thus, the main objective of this paper is to provide a comprehensive review of the body of literature available for the use of the solar thermal (ST) energy in DH networks. The paper

presents an overview of solar district heating and cooling separated into four different types of system. These installations have in common the harvest of solar thermal energy with solar collectors and the connection to a thermal district network to deliver that energy to the load.
The paper addresses centralized and decentralized SDH, block heating and solar district cooling systems including as well their control and integration.
This work considers solar collectors and energy storage as the two main elements in a solar district network system. Thus, the two main types of mounting for the solar collector field are discussed in this work. In the same way, the alternatives of energy storage are explained along with their main features.
The paper starts with a general overview of SDH itself addressing the history of the use of heat in DH networks, introducing the background in solar thermal use in DH as well as defining and describing the typologies for different types of systems. There are then chapters on District Heating (with both centralized and decentralized collector fields), Block Heating and District Cooling, each with an example to give a more detailed insight into state-of-the-art systems and technology. The two main components in the systems, collectors and storage, are dealt with in separate chapters before other aspects and trends are discussed.

2. GENERAL OVERVIEW OF SDH

2.1. District Heating

Fundamentally, the underlying idea of the DH concept is to recycle heat that would otherwise go to waste, enabling a more efficient use of primary energy and hence, natural resources. For this reason, countries (e.g. Sweden and Germany) that have energy-intensive industries based on processes like metallurgy, petroleum and paper production have traditionally had strong ties to DH. Likewise, countries (e.g. Denmark and Finland) that traditionally have been dependent on fossil-fuel imports have developed equally strong bonds with DH.
Geographically, DH systems are most widespread in the northern hemisphere, predominantly (descending order) in Europe (northern and eastern part), Russia, China and North America. Countries like Denmark, Sweden, Finland together with Poland and the Baltic states have the largest market shares (>40%). Eastern European countries generally have many systems, due to the influence of the former Soviet Union, where DH was under development early as part of the planned economies.
Common for all types of DH networks is that they require some way of transferring heat between distribution network and consumer. Substations (hydraulic equivalents of electric transformers in electricity grids) contain heat exchangers and other hydraulic components used to isolate the consumer from the heat distribution network. In this way, energy (heat) can be transformed from a higher exergetic level to a lower level, usually by reducing temperature and other related parameters. The efficiency of the heat transfer is dependent on the substation design as well as difference between supply and return temperatures (ΔT). Modern substation technology is designed for annual supply/return temperatures of 69 °C/34 °C (ΔT=35 °C), and modern DH systems are so far able to work within +5 °C of these temperatures [16].
The operating temperatures of DH networks are usually part of the national regulations and design guidelines, and thus may vary from country to country. An overview of some national design temperatures is given in Table 1 [17]:

Table 1. Overview of some example national design temperatures for heating networks.

	Temperatures [°C]		
Country	**Supply**	**Return**	**DHW**
Denmark	70	40	<60
Finland	70	40	55
Korea	70	50	55
Romania	95	75	-
Russia	95	75	50
United Kingdom	82	70	65
Poland	85	71	55
Germany	80	60	55

2.2. Background

For reasons of natural resource depletion, environmental protection, energy security and long-term economics, many governments have set goals for increasing the contribution of renewable energy sources to the national demand. In Europe, space heating (SH) and domestic hot water (DHW) account for about 80% of the energy needs of residential buildings [18]. As the temperatures required for these purposes are relatively low, there is a huge potential in exploiting solar energy through solar collectors. ST technology is widespread in the single-family house sector, while larger installations for DH are still rare, except for a few countries. Presently, large solar collector systems (>350 kWth) represent approximately 1% of the market [19]. Nevertheless, increasing the installation size can be advantageous, as this usually leads to an enhancement of the performance and a decrease of the investment cost per unit area.

A prerequisite for a large solar collector field is a DH network, which functions as a heat sink with almost infinite capacity, where the thermal energy can be discharged. A key role for the successful integration of solar heat with DH is played by the DH operating temperatures. Both supply and return temperature should be as low as possible, so that the solar collectors operate at higher efficiency and heat losses from the DH network are reduced.

Figure 1 shows the historical evolution of the number of installed solar heating plants for DH applications. Currently there are approximately 5000 DH systems in operation in Europe, supplying 10% of the total heat demand [20], but only about 150 solar district heating (SDH) systems [21], most of which have solar fractions no larger than 20%. The European Union has set a target of 1% solar fraction in DH by 2020 and of 5% by 2050 [22].

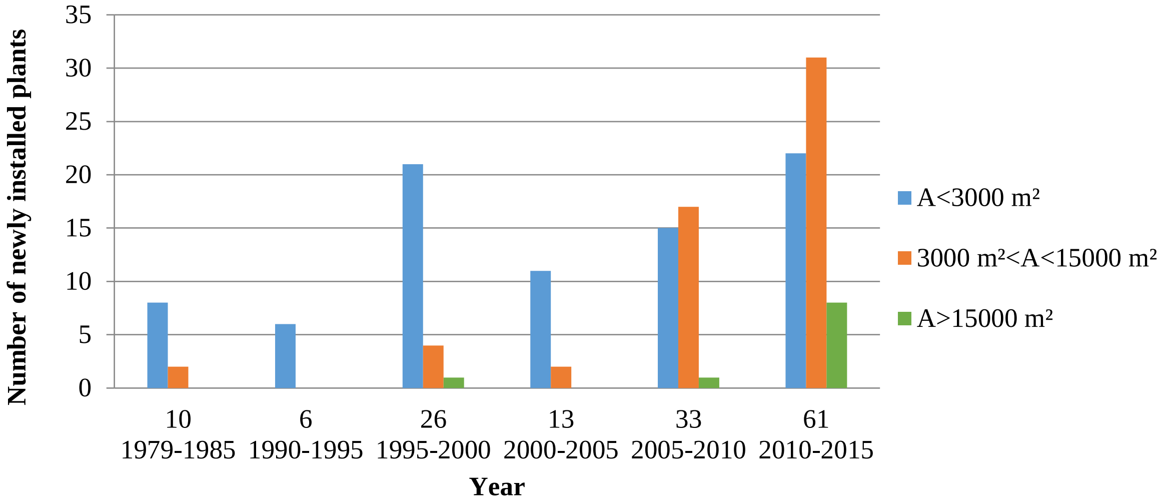


Figure 1: Historical evolution of the number of newly installed solar heating plants in Europe. The plants are grouped according to their aperture area. The total number of newly installed plants is indicated above each time period [23].

Denmark is currently the frontrunner in the field of SDH with 79 plants installed at the end of 2015 [24]. In other European countries, much smaller markets exist. Sweden was the pioneer in the early years of development of SDH (1979-1995), when it installed 12 of its current 23 plants [23,24]. Austria has seen a rapid development in SDH in the last ten years and is now the third country for installed collector area [23] with 28 systems larger than 500 m^2 supplying DH or block heating networks [24]. In Germany, 25 plants are currently in operation [24]. Of these, many were installed in the period 1995-2005, stimulated by the 10-year long governmental programme Solarthermie-2000, launched in 1993 [11]. Smaller markets in terms of installed collector area exist in Spain (16 plants), France (15), Greece (14), Poland (14) and Switzerland (9) [24].

Most large scale solar applications are connected to DH systems, but there is an increasing number of solar cooling plants supplying with chilled water instead of hot water [25], but most of these are not district cooling networks with several customers.

2.3. System typologies

There are three parts to consider when including ST into a system:

- the solar circuit itself (collector, piping, pump, valves and expansion vessel),
- the integration of the solar circuit into the overall system and
- the flow control in the solar circuit and the control of the rest of the DH system.

The solar circuit itself can, in principle, have the same design for all types of system typology for DH, but practical details vary depending on whether the collector is ground or roof mounted. The main differences between typologies are in system integration, and many different options have been studied. The flow control in the collector circuit is dependent on this system integration, but only two strategies are used in practice: constant, normally high flow rate to maximize solar gain; matched flow so that the collector field supplies a desired temperature, normally the supply temperature in the DH network.

If the ST system will only supply a small part of the DH demand, then the system integration is relatively simple, no matter what the system typology is. With very low solar fraction,

<50% of the daily summer demand in the DH network on a cloudless day, no storage is required for the solar heat other than in the DH network itself [26]. With higher solar fractions, storage is required somewhere in the system. The choice is centralized or distributed storage, leading to different system typologies and a need for an overall plan for the whole DH network. In this article, three different typologies are distinguished (*Figure 2*).

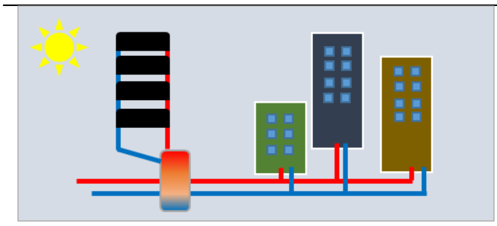
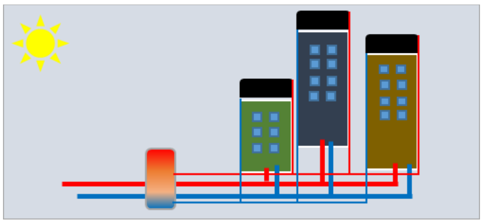
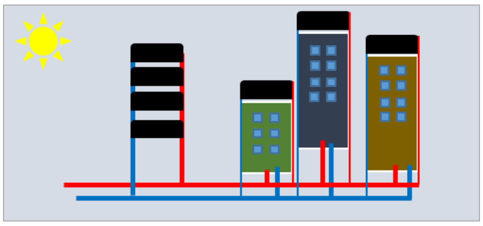
Solar assisted district heating – system typology	
	Centralized: Central storage and central solar collector field.
	Centralized: Central storage and distributed solar collector field
	Decentralized: Distributed solar collector field(s) without storage (feed-in)

Figure 2: Overview of different system typologies in SDH systems

The following chapters will cover:

- **Centralized** systems with central storage and a central (usually ground-mounted) solar collector field connected to the network supply.
- **Decentralized** systems without storage and distributed solar collector field(s) feeding into the network supply pipe. These systems usually cover a smaller solar fraction and are typically mounted on available roof-space, although they can be ground-mounted as well.

  Decentralized systems may also feature distributed storage(s) and distributed solar collector field(s) connected to the network load side. However, these systems are not treated in this article.
- **Block heating** systems are treated in this article as smaller DH systems. The solar integration varies with system concept and may consist of different typologies: centralized storage and collector field, centralized storage and distributed collector field or mixed typologies, where there can be both centralized and distributed collector fields and storage.

3. CENTRALIZED SDH SYSTEMS

In centralized SDH systems, the solar collector field is usually installed close to the main DH plant, which hosts the auxiliary energy system (Figure 3). The European market of centralized SDH systems is dominated by ground-mounted flat plate collectors, which represents more than 90% of the total area [23,27]. Unlike block heating systems, most solar collector fields for centralized SDH are added to existing DH networks, in order to reduce the use of conventional fuels in the main heating plant.

From a technical point of view, solar heat can be combined with all other fuels for DH, but some of them are more suitable for environmental and economic reasons [28]. The auxiliary energy system often relies on natural gas (CHP plants or boilers) or biomass [27,29,30], and is turned on when solar energy cannot completely cover the heat demand. The solar collector field is usually installed in parallel with the auxiliary energy system (Figure 4). In case of high solar radiation, the collector field provides the entire temperature rise required by the DH network. If the solar radiation is not sufficient, the warm water from the ST system cannot be injected directly into the DH network. In this case, the auxiliary energy system supplies additional energy to increase the fluid temperature to the DH supply temperature. The heating plant is equipped with a storage, which can store heat from the auxiliary energy system and the solar collector field. The size of the storage plays an important role in the solar fraction that the system can achieve (see Section 8).

Large solar heating systems with capacity larger than 350 kW represent a very small portion (about 1%) of the European market for solar heat, which is about 2-3 GW_{th} per year [19]. Denmark is the leading country in this sector [8] with 77% of the collector area installed in the European solar heating plants at the end of 2015 [24]. With about 800,000 m^2 of collectors and 79 plants in operation at the end of 2015 [24], this country is a unique example for a mature and commercial SDH market without subsidies. A key role in this development has been played by the widespread use of DH, which supply about 60% of the heating demand of buildings [8], and high taxation on fossil fuels [31].

The size of the installations varies significantly depending on the DH load, aimed solar fraction, presence of seasonal storage and economic considerations. Collector fields with nominal capacity between 700 kW and 50 MW are installed in Europe [23,27].

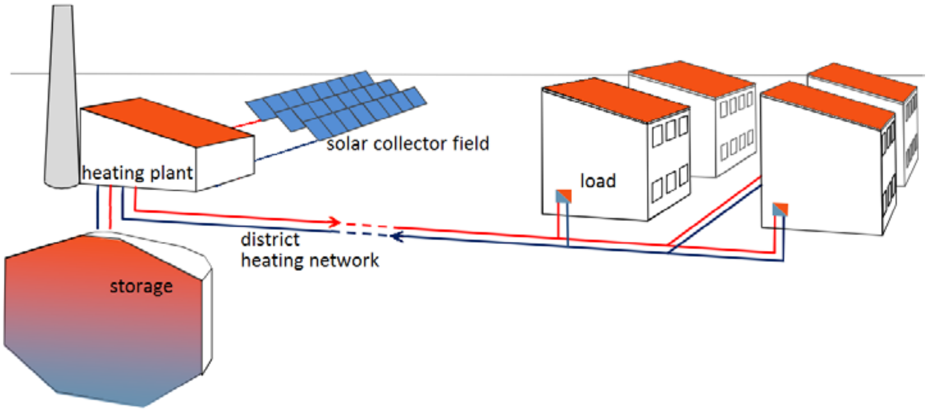


Figure 3: Scheme of a centralized SDH network at a DH plant (adapted from Solites [32]*).*

3.1. **Example (Braedstrup, Denmark)**

3.1.1. System description

An example of centralized SDH system is given by the Danish plant in Braedstrup. This has a yearly heat production of 40-45 GWh and supplies SH and DHW to 1400 buildings (290,000 m^2), through a 49 km long network. Typical supply and return temperatures are 75 °C and 40 °C respectively. The original plant, consisting of two gas fired CHP engines, two gas boilers and a 2000 m^3 tank, was expanded in 2007 with 8000 m^2 solar collector field. In 2012, other 10600 m^2 collectors were installed, together with a 5000 m^3 buffer tank, a 19000 m^3 seasonal borehole storage (5000 m^3 water equivalent), 1.2 MW_{heat} heat pump and 10 MW electric boiler [33]. A further expansion of the collector field, borehole storage and heat pump capacity is planned, to completely replace the use of natural gas in the future. Figure 4 shows a schematic of the current plant. The control strategy of the entire plant aims at minimizing the heat production cost and maximizing the income from selling the electricity produced by the gas engines. Consequently, the ST system has the highest priority of operation whenever possible, as it delivers almost free heat. Gas engines are run when the electricity prices make their operation profitable. The plant is run differently depending on the season. In winter, the return of the DH network is supplied directly to the large tank, while the small tank is used to discharge the borehole storage. In spring, the large tank is progressively charged and, when it is full, the plant switches to “summer mode” and the DH return goes into the small tank. When the large tank is more than 50% charged, some of its water is extracted and sent to the borehole storage to charge it and then returned to the connection between the two tanks. The heat pump and the electric boiler are turned on when the electricity price is very low. When it is not suitable to use the above mentioned technologies or they cannot cover the heat demand, gas boilers are turned on.

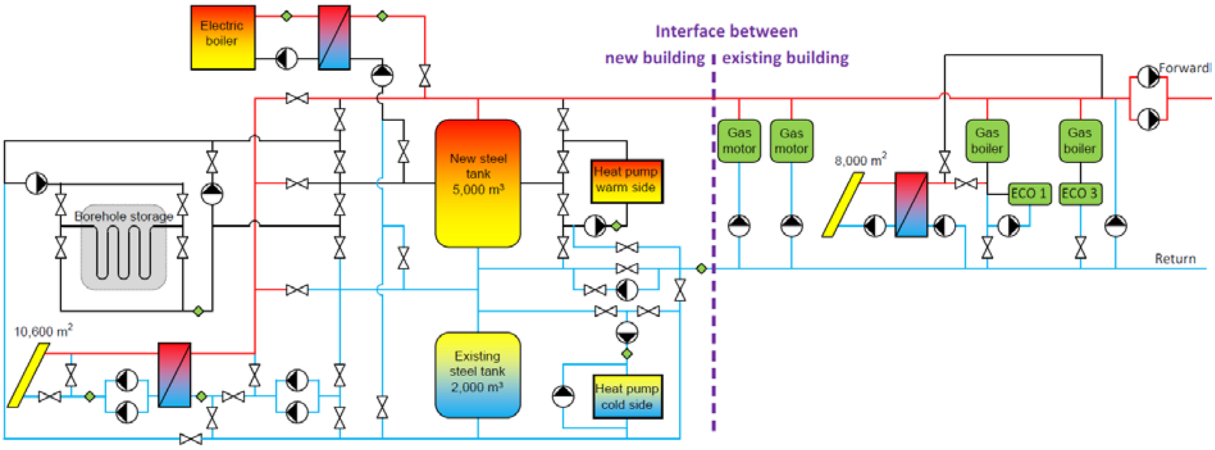


Figure 4: Principle diagram of Braedstrup heating plant [33].

Monitoring data of the different plant components from 2012 were made available by PlanEnergi [33]. It must be noted that the new solar collector field was put into operation only in April 2012 and the borehole storage in May 2012. Of the 40 GWh delivered, 15% were provided by the solar collector field, 58% by the gas boilers, 20% by waste heat of the gas engines and 7% by the electric boiler. Negligible contribution came from the heat pump and borehole storage, most likely because a borehole storage needs a couple of years of charging before being able to release useful energy. In the months of July and August, solar energy covered more than 70% of the total heat demand and the gas boilers were barely used. The yearly energy output of the solar collector fields was 435 kWh/m^2 and had an average efficiency of 36% [33].

3.1.2. Economy

The costs of the main components added during the extension in 2012 are shown in Table 2. The collector field represented the main voice of expense, with a specific cost of about 300 €/m^2 including land and pipes. The borehole storage had a cost of about 50 € per cubic meter of water equivalent.

Table 2: Main cost for the extension of Braedstrup heating plant in 2012 [33].

Component	**Cost [k€]**
Solar plant, transmission pipe and tank connection	2933
Land	240
Piping of the water loop side	158
Borehole storage (drilling, pipes, lid)	262
Test drilling and laboratory (borehole prestudy)	37
Heat pump	101
Accumulation tank	96
Electric boiler + connections	663
Measuring equipment	37
Control system	445
Total	**4972**

Based on the decrease in the average installation price in the last years (see Figure 13), the cost of a solar collector field with similar characteristics to Brædstrup can be expected to be 10% - 15% lower (specific cost of 240 €/m2 [34]) if installed in 2016. In addition, the borehole storage would likely have a lower cost due to experience acquired with this type of installation. However, precise costs cannot be estimated because of the lack of new installations of this type in the last years.

4. DECENTRALIZED (FEED-IN) COLLECTOR FIELDS

In this article a ST system that is connected to a DH network outside the main heating plant is classified as a decentralized system, even when the distance from the feed-in point to the main pumps in the DH system is only some meters [35]. The collector field is normally roof-mounted, but systems with ground-mounted collectors also exist. Nearly all decentralized ST systems are connected to existing DH networks.

Unlike centralized system, decentralized plants are often, but not necessarily, located where there is a load and thus an existing DH substation.

Decentralized systems can be connected to the DH network in different ways (Figure 5). The most common connection is Return/Supply (R/S), where water from the return DH pipe is heated up and pumped back into the supply pipe. If there is an existing substation at the feed-in site, no new service pipes to the DH network are required. The flow in the service pipes between the substations and the DH network can flow in both directions, the direction being dependent on the heat balance between the solar heat feed-in and the required heat at the load substation.

If a Return/Return (R/R) feed-in system is connected to the DH network at the same place as a substation, the normal supply and return service pipes are not sufficient. As shown in Figure 5, a third pipe, taking the solar heated water back to the DH return pipe, is required. The R/R connection also increases the return temperature of the network, which is undesirable in many DH systems. If the central heating plant includes CHP, heat pumps, ST and exhaust gas condensation, the efficiency of these production units decreases if the return temperature increases. Conversely, if the central heat production unit is not affected by higher return temperatures, this issue of decreased efficiency does not occur, as long as the heat load is higher than the lowest recommended load of the heat production unit. This is one of the main reasons why the R/R connection is less common than R/S connection. However, the control in an R/R connection is simpler, as it can use a constant flow rate, whereas in an R/S connection the feed-in flow rate is varied to maintain a certain supply temperature to the network, which is specified by the network operator.

Theoretically, supply/supply (S/S) and supply/return (S/R) connections are also possible, but these present some disadvantages and are only used in exceptional circumstances, such as to avoid overheating in the collector field. Hence, they are not covered in this article.

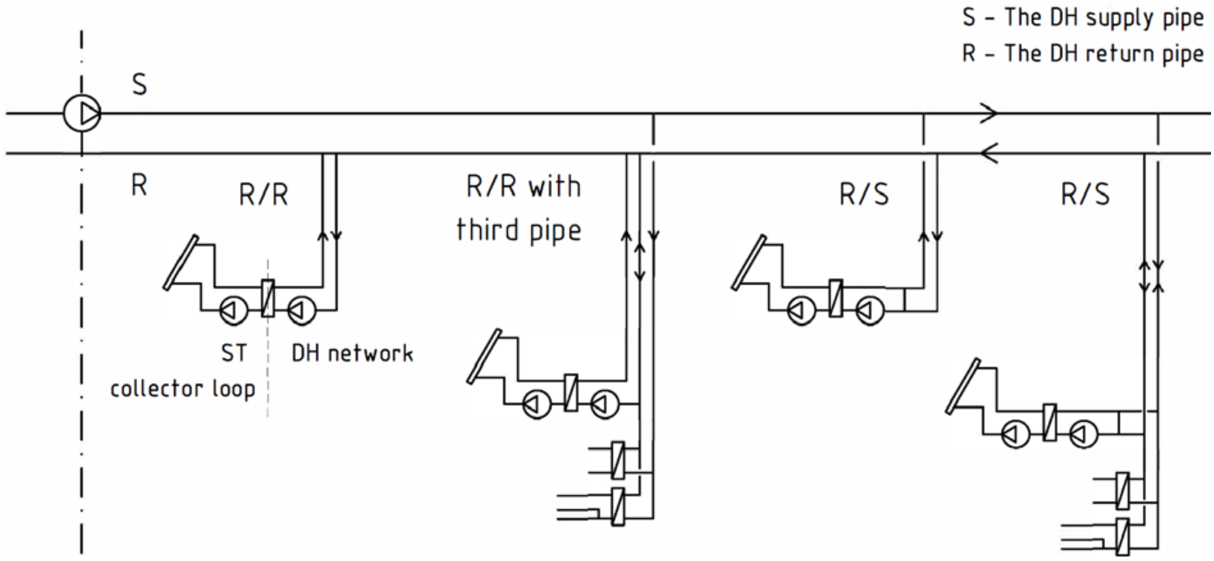


Figure 5: The most common ways to connect decentralized ST systems to the DH network.

In Sweden, the first R/S systems were built in 2000 in conjunction with the building exhibition Bo01in Malmö. Since then, around 30 R/S systems have been built in Sweden. Twenty-two of these plants, varying in size from 42 to 1128 m^2 collector area, are analysed in [36]. The authors conclude that several of the plants were not performing as well as planned. Some had maintenance issues, while others had been working reliably and as expected. There were several different designs, mostly in terms of control of the temperature supplied to the DH network. Some R/S substations had been designed by consultants and built on site, while several were supplied as pre-fabricated substations, sized according to the collector area. Lennermo et al. [37] found that some of the systems had large variations of outlet temperature in the collector loop and feed-in heat power over time. The variations have also been found in

R/S feed-in systems with heat generation systems other than solar. Flow and heat power variations in the feed-in system can cause problem in the DH network, especially if the feed-in system is large. If the feed-in system is small compared to the DH system, problems are less common. The problem with temperature and heat power variations is more difficult to solve if the differential pressure is high and the feed-in flow is low or it has a large variation due to the characteristics of the heat power generation, as it is in a ST system [38].

Hassine and Eicker [39] studied R/R, R/S and S/S connections through simulation of the DH network of the Scharnhauser Park (Germany) with 584 consumers. They focused on the ST contribution and on the impact of the geographical location of the ST in the DH system on heat users, not located near the ST, and on the central plant. They conclude that the R/R connection was the most efficient option from a ST heat production point of view, but also that the S/S connection could give benefits, if the ST system was located near the edge of the network, where the supply temperature is lower compared to near the centre of the network due to heat losses. Hassine and Eicker [40] also studied control aspects of the main DH pump in a network with ST system with R/S connection. They found that pressure control using a limited number of pressure sensors was not reasonable, whereas volume control was.

In Austria, the company Solid has installed large decentralized solar plants in Graz. The system at the UPC Arena consists of 1407m^2 roof-mounted flat plate collectors. These are connected to the main DH network with an R/S connection with variable speed pump and two-way valve [41]. The system at Wasserwerk Andritz has 3855 m^2 ground-mounted flat plate collectors as well as a 60m^3 water storage, and is thus a decentralized system with distributed storage. The collector field is connected R/S to the DH network but also in parallel to the local store and therefore supplies heat to the local buildings at the water works as well as to the DH network [42]. Based on the experience of these systems, Holter [43] claims that 100% of the summer load for the Graz DH network (~15 MW) can be met by waste heat together with solar energy, preferably using systems like that at Wasserwerk Andritz with feed-in to the DH network as well as on site use of the solar heat.

Paulus and Papillon [44] made a techno-economic analysis of a range of substation designs based on simulations of the local load and different DH network operating temperatures. Nine different substation architectures were simulated, ranging from purely feed-in connection to combined systems with both DH feed-in and solar heat use on site with thermal storages supplying both DHW and SH. They used an R/R connection for all architectures. They conclude that low DH return temperatures favour both the efficiency of the solar plant as well as economics for all architectures. For higher return temperatures, some architectures reduce the loss of thermal efficiency of the solar field due to the higher operating temperatures.

In Denmark, the focus has been on large centralized solar installation, but there are also a few decentralized plants installed. The plant at Avedøre has 750 m^2 roof-mounted flat plate collectors on top of a large multifamily house with a R/S connection [45]. The plant at Herredsvej/Månepletvej in Hillerød has 3000 m^2 ground-mounted flat plate collectors with R/S connection.

4.1. Example (Vislanda, Sweden)

The system in Vislanda (Sweden) was installed in 2009 as a roof-integrated flat plate collector field of 344 m^2, located on a single building. The substation is a pre-fabricated unit with R/S connection where the feed-in flow is controlled by a variable speed pump and a motorized two-way valve, as shown in Figure 6 [36]. The system is owned by the housing company Allbohus, and feeds into the DH network operated by Alvesta Energi, with which Allbohus has a net-metering contract. According to Dalenbäck et al. [36], the system did not work properly during the measurement campaign in 2011-2012, but it was fixed in 2013. The authors conclude that the DH operating temperatures are sometimes too high, due to the nearby input of waste heat from an industrial plant into the return pipe of the DH network. This results in a relatively poor operation of the collector field.

At the time of the installation, the owner had already planned to replace the roof of the building. Thus the net costs for the system were relatively low, after subtracting the cost for a normal roof from the total investment cost [42]. The company that won the tendering contract produced large collectors, which were integrated in the roof. The total cost of the turn-key system was 178 k€ without VAT, resulting in a specific cost of 516 €/m^2. This value is relatively low for such a small system [42], but still much higher compared to large centralized systems in Denmark. For example, the collector field of 8000 m^2 in Braedstrup (see Section 3.1.2) had a specific system cost of 300 €/m^2, including land and service pipes.

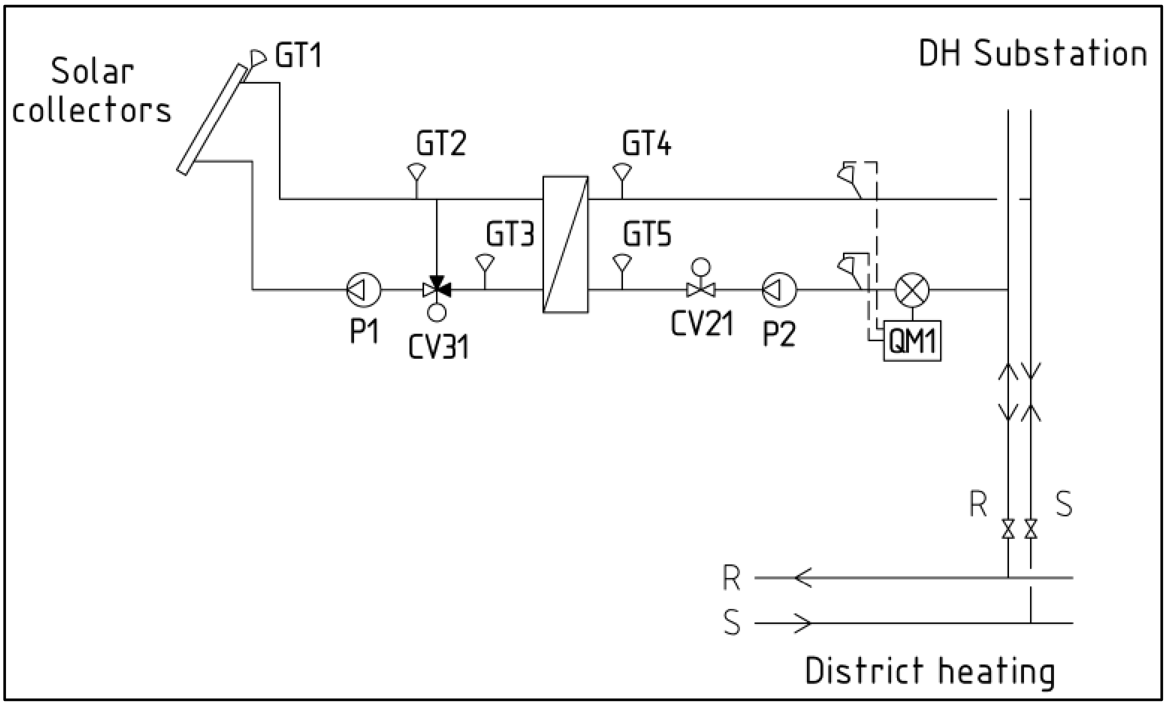


Figure 6: Schematic of the pre-fabricated R/S substation of the feed-in system in Vislanda, Sweden.

5. BLOCK HEATING

Block heating systems are small DH networks. The integration of a ST system into a block heating network can be a cost-effective solution, especially for new low-energy residential areas. This is why nearly all solar block heating systems are built at the same time as the buildings. Areas of around 10-100 one-family houses or up to 400 dwellings in multi-family buildings exist, such as in Friedrichshafen [46]. The typical boiler capacity in this kind of systems is between 50 kW and 10 MW [47]. Normally, systems with diurnal storage have a design solar fraction of around 20%, delivering 80%-100% of the DHW load in the summer months. Solar assisted block heating systems have been built for more than 30 years [48]. Studies have mainly focused on lowering the heat losses, increasing the efficiency and solar fraction of the ST system, while decreasing the costs.

In Germany, the Solarthermie-2000 program stimulated the installation of this kind of systems with different sizes. It proved to be possible to reach high solar fractions, especially using seasonal storages. Solarthermie-2000 and Solarthermie+ resulted in several reports on experiences and recommendations for solar block heating systems [11]. In order for seasonal storage to be feasible, the network should consist of at least 100 dwellings [49]. Based on TrnSys simulations, Sibbitt et al. [50] found that the most profitable solution for a smaller block heating network with seasonal storage would be:

- Individual DHW with solar heat and auxiliary heating, and
- A low temperature distribution network supplied by centralized solar panels connected to a seasonal borehole storage.

A system based on this design was built for a housing estate of 52 houses in 2007 in Drake Landing (Canada) and achieved a solar fraction higher than 90% after 5 years of operation [50].

5.1. System Integration

Solar block heating systems can have different integration typologies. The collectors may be located at or close to the central heating plant, but more often they are distributed on the roofs of the buildings supplied by the DH network. These distributed collector fields can either be connected to a central store or use a mixed typology with both centralized and distributed storage. As the distribution network and the collectors are normally designed and built at the same time as the buildings, it is possible to optimise the integration of the ST system. Extension of the housing area together with the network is relatively common after the main network has been installed.

Clever storage design, sizing and strategy are necessary to increase the system efficiency and ensure a stable operation. It is important to have a good coherence between solar feed-in, boiler operation and storage temperature. Accurate temperature monitoring is essential to obtain correct operation [29]. As for any ST system, one of the most important factors to obtain high efficiency is a low return temperature from the distribution network. Three different systems in Germany (Hannover, Hamburg and Steinfurt) were investigated in [51]. In all three systems, problems were found on the consumer side of the network. In all cases, it was possible to lower the network return temperature by considering better-sized components, ensuring that the installed components worked properly, and optimizing the control strategy with regard to energy efficiency.

Besides the network temperatures, other two parameters affect the network heat losses: thermal insulation of the network pipes and heat density of the network. Dahm [52] simulated different distribution networks, types of substations and house heating systems for a block heating network in Swedish conditions, using models calibrated from two networks. The study showed that the heat losses contributed very little to the annual heat cost, and that a network with higher operating temperatures (due to high temperature radiators) has similar losses compared to a network with lower operating temperature. In fact, using smaller diameter pipes in the DH network, when operating at higher temperatures, reduced the overall heat transfer surface. The heating system in the houses had the highest impact on the annual heat cost. Substations with local DHW storage were shown to be the least cost-effective solution.

The Swedish municipal housing company Eksta has been building solar assisted block heating systems since the 1980s, in cooperation with engineers and designers. The systems have been designed and built at the same time as the houses, and all of them have roof-mounted collectors. One of them, in Särö, includes a small seasonal water storage of 650 m^3 with 750 m^2 roof-integrated collectors. The design solar fraction is 35% [53]. The heat distribution type Grudis [54] was developed to decrease the cost and have acceptable heat losses for small low-density networks by delivering SH using a DHW circulation loop between a substation and the houses. This type of system was used in Vallda Heberg, described in detail in Section 5.2.

Delivering heat with “pulses” is another way to decrease heat losses. In this way, the DH network is used only 20%-50% of the time to charge distributed storages. This was successfully implemented in Hjortshøj (Denmark), where distribution losses were decreased by 20%-27% compared to a system with continuous flow [55]. To further decrease distribution losses in the summer period, distributed solar collectors were installed for individual DHW preparation. The overall distribution losses are decreased by 50% [55]. In this way the network can be shut off in summer, making the maintenance easier [56]. These strategies have only been tested in block heating systems, as they require specific substations for all consumers, and their implementation is only realistic in new networks.

Several piping layouts exist. The most appropriate layout depends on the properties of the heating plant and the heat density of the network. This has been investigated in Germany [57] and in Austria in the MOSOL-NET project. Based on computer models and experiences, several recommendations have been given on network design, collector positioning and optimal control [58]. The recommendations of the German and Austrian studies are rather similar, although the detailed design is very system dependent:

- six pipes (two each for DHW, SH and solar) for dense heating networks;
- four pipes (two for distribution of DHW&SH and two for solar) for large networks, also including long-term storage;
- three pipes (two for distribution of DHW and SH, one for solar supply). The input to the collectors is taken from the distribution return pipe, while the collector outlet fluid flows into the third pipe. Obviously, the third pipe cannot use water/glycol mixture for frost protection.

Advanced control strategies can significantly increase the system efficiency. An innovative solution has been tried for a small network with low energy buildings in Gleisdorf (Austria) [59]. The network is operated 22 hours/day at 40 °C for SH, and 2 hours during night at 65-70 °C to prepare DHW in decentralized hot water storage tanks.

Beckenbauer et al. [60] analysed the solar retrofitting of a block heating system, comparing different centralized and decentralized setups. Mainly due to high network return temperature, a decentralized solution with direct DHW preparation was found to be optimal for this case.

5.2. **Example (Vallda Heberg, Sweden)**

The Vallda Heberg area, built by the housing company Eksta in Sweden, consists of 26 single-family buildings, four multifamily buildings (4 apartments per building), 6 terrace houses with in total 22 units and also a nursing home for elderly people with 64 apartments. The total heated floor area is about 14000 m^2 and the measured yearly heat demand is 621 MWh [61]. A kindergarten and a few commercial buildings are planned to be added in the next future. All buildings are designed as passive houses with mechanical ventilation heat recovery, and thus the heat demand is low. In the houses, heat is supplied by floor heating in the bathrooms and an additional water/air heat exchanger in the supply air to the building.

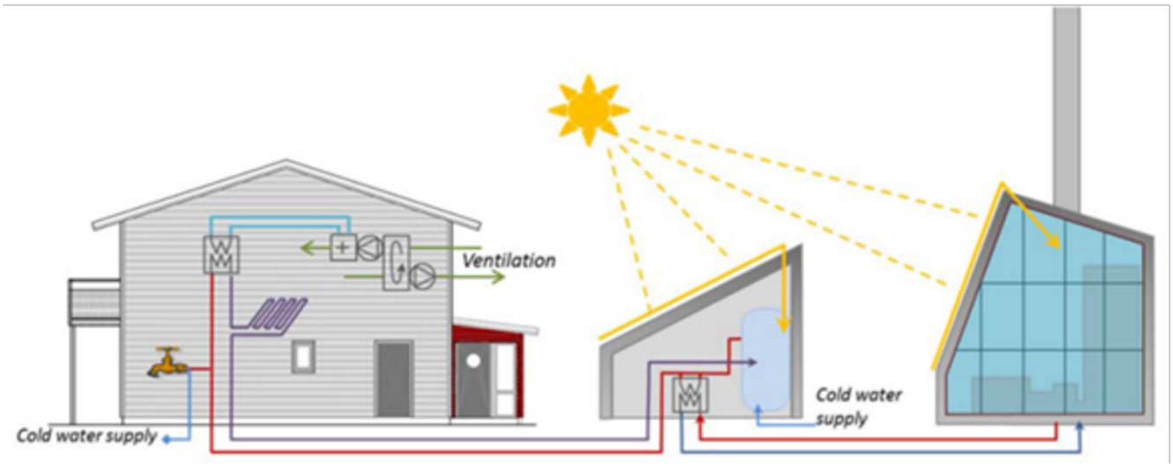


Figure 7: Partly decentralized system in Vallda Heberg showing an example house (left), example substation with roof-mounted collectors and storage (middle) as well central heating plant with rood mounted collectors (right). [Anderson/Hultmark: [61]*].*

The local DH system comprises a central heating plant with a 250 kW wood pellet boiler and four substations. Each substation supplies a part of the housing estate and is connected to its own collector array (see Figure 8). In the central heating plant and in each substation there are buffer storage tanks. There are 108 m^2 evacuated tube solar collectors on the heating plant and 570 m^2 flat plate roof-integrated solar collectors in connection to the substations (see Figure 7). The distribution networks from the four substations to the dwellings are of Grudis type [54], which essentially is a DHW circulation loop with direct connection to the houses. The floor heating in the houses is a part of this loop and. To avoid risk of legionella, the entire loop is maintained between 50 °C and 60 °C. For this reason, there is no flow control in the floor heating loop. This results in a very simple and cost-effective heating system, as well as a simple distribution network with plastic pipes. However, as the buildings are passive houses, the energy density of the network is low. The authors report that the 2014 monitored data for substation 1, with 142 m^2 collector area supplying 19 single family houses, show that the combined losses for the substation itself and the DHW circulation loop were 24% of the total demand (SH, DHW and losses). The specific collector yield for the collectors connected to substation 1 was 299 kWh/m^2/year resulting in a solar fraction of 31%, with 90% of the solar heat supplied from the collectors connected to the substation and only 10% coming from the collectors at the main boiler plant.

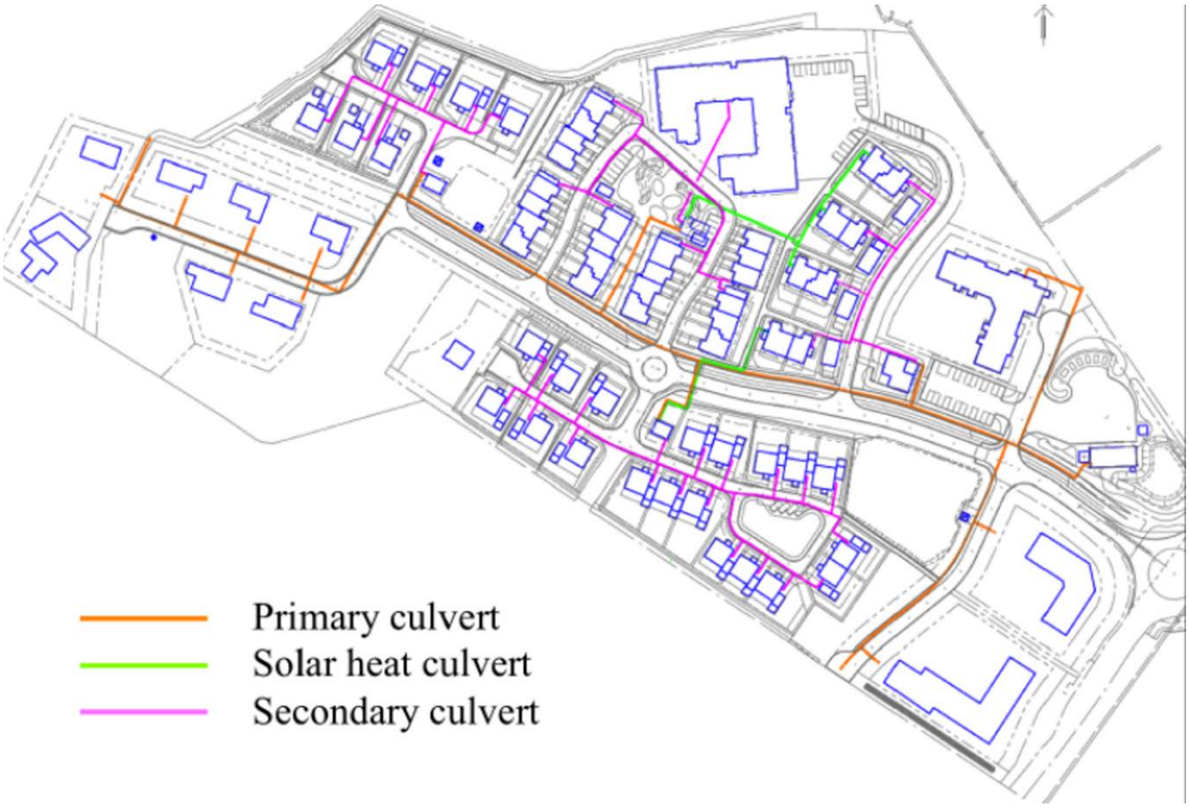


Figure 8: Vallda Heberg area with central heating plant (red oval, right), four substations (red circles),distribution pipes for heat supply (brown) and -load (violet), and solar heat (green) between the 4 multifamily buildings and substations 1 (middle, bottom) and 3 (middle, top).

6. DISTRICT COOLING

A district cooling system (DC) distributes chilled water in buried pipes and delivers cooling energy to the substation of the users in order to meet their cooling requirements [62]. In DC, a lower amount of energy is supplied with the same amount of liquid compared to DH due to the lower temperature difference used in DC. Usual temperate difference is about 6 ºC (usually 6 ºC/12 ºC as supply/return temperatures) or at most 8 ºC (4 ºC/12 ºC) for ice based systems [17]. Consequently, DC pipes are generally larger compared to DH. A higher temperature difference may be used to lower the power consumption of the distribution pump, but this will increase the heat gains of the pipes [62,63]. It is generally recommended to find optimal supply/return temperatures in order to optimize the efficiency of the generating cooling system and of the overall DC, as wrong temperature configuration may lead to an excessive energy consumption from the cooling system [64–66].

Shimoda et al. [67] showed that DC that produce large-scale and collective cooling energy have a higher efficiency than conventional systems at individual premises. The total energy consumption of a DC may be 8% lower compared to individual systems. The current cooling demand worldwide, despite being much smaller than the heating demand, is growing exponentially. It is expected that by 2020 at least 60% of commercial and public buildings in Europe will be equipped with cooling appliances. The residential sector is less often supplied by DC, although this may change as the climate warms and incomes rise [68]. At least 15% of electricity consumption worldwide is used for cooling purposes [69]. Today DC in Europe represents about 2% of the total cooling market, corresponding to approximately 3 TWh cooling [70]. The market penetration of DC shows great diversity. This market has emerged quite recently and is consequently less developed than DH. However, it has been growing rapidly in the last decade, with a tenfold growth in installed capacity. Although DC is not yet well established in Europe, it is well developed in North America [71]. Solar cooling is a promising technology to be included in DC, as solar energy is widely available and matches the cooling demand well [72].

6.1. System integration

The main components comprising a solar DC are: solar collectors, cooling system, distribution network and storage. The overall system performance depends on how the different parts interact. The interaction between solar collector field and cooling system is generally the most critical [73]. In fact, the efficiency of the collector field decreases with operating temperature, while the efficiency of the thermally driven cooling process increases. Differently designed collectors operate at different temperatures, so it is important to match the collector type with the chiller type. Given a certain range of required supply temperature from the chiller, most kinds of solar collectors may find their application in solar cooling. The most commonly used combinations are shown in Table 3 [69,72–76]. In Table 3 the presented COP_N values are the maximum experimental values found in literature.

Table 3: Typical matching between solar collector types and sorption technologies.

Sorption technology	Required T_{in} [°C]	$T_{Chill,out}$ [°C]	COP_N	Solar Technology
Absorption				
Single effect	75-90	LiBr: 4 – 7	0.7	Flat-plate
Double effect	120-160	NH_3: < 0	1.2	Evacuated tube, concentrating collector
Triple effect	220		1.7	Concentrating collector
Adsorption				
Silica-gel-Water	<85	0 – 4	0.6	Flat-plate
Carbon-Methanol	>120	-12 – -2	0.4	Evacuated tube, concentrating collector
Carbon-Ammonia	>150	-10 – 0	1.19	Concentrating collector
Zeolite-Water	>200	-8 – 0	1.6	Concentrating collector

In principle, the high temperatures reached with solar concentrators that occupy a smaller area lead to an increased COP and a reduction of the system cost [72]. Non-concentrating collectors are often used for their low cost [25], although they can only reach temperatures which are compatible with the low efficiency sorption technologies.

Thermal storage can be either a heat energy storage (HES) for the solar heat or a cold energy storage (CES) supplied by the cooling system [72]. Three configurations are possible: CES, HES and CES+HES. The main advantage of the last configuration is the perfect match between demand and cooling generation, and the increase of system performance through a more constant heat supply to the thermally driven chiller, which leads to an optimization of the COP_{solar} [72].

In [77] two different systems for a DHC in Madrid (Spain) are compared through their payback period. The first system comprises three engines of 730 kW_{el} and a backup boiler of 670 kW_{heat} as generation system, and two double effect absorption chillers of 1.1 $MW_{cooling}$ and five backup compression chillers of 1 $MW_{cooling}$ as cooling system. The payback is 10.6 years. The second system comprises 2000 m^2 flat plate vacuum collectors, three engines of 730 kW_{el} and a backup boiler of 200 kW_{heat} as generation system, and a double effect absorption chiller of 3 $MW_{cooling}$ and a backup chiller of 4 $MW_{cooling}$ as cooling system. Assuming a 60% subsidy for the solar collector field, the payback time is 11.6 years.

There are an increasing number of large solar cooling systems [25], many of which are installed and operated by ESCos (Energy Service Companies), principally Solid from Austria [78]. However, most of these systems supply single consumers and thus are not strictly solar DC.

6.2. Example (ParcBit, Spain)

The ParcBit solar district heating and cooling system is located in Mallorca (Spain) and run by Sampol Ingeniería y Obras. This system provides heating and cooling to the University of Balearic Islands and the Innovation centre Parc Bit. The power plant comprises multiple generation systems for heating and cooling, as well as a storage. In Table 4 key figures provided by the operating company are listed.

Table 4: Parc Bit main figures.

	Element	Technology	Installed Figure	Flow	Yearly demand	Cost per unit
Generation	IC Motor (2)	Diesel	2 x 1.36 MW_e	76 m^3/h	68.1%	450 €/kW
	Solar Collectors	Flat Plate	0.7 MW_h – 900m^2	35 m^3/h	2.4%	350 €/m^2
	Biomass	Wood chip	1 MW_h	65 m^3/h	21.5%	600 €/kW
	Burner (2)	Diesel	1.2+0.8 MW_h	115 m^3/h	8.0%	70 €/kW
Cooling	Absorption (2)	Single. Li-Br	1.3 + 0.64 MW_c	180+65 m^3/h	43.2%	150–300 €/kW
	Electric Chiller	Compressor	1.2 MW_c	170 m^3/h	18.6%	55 €/kW
	Electric Chiller	Screw	1.3 MW_c	155 m^3/h	38.2%	55€/kW
	Cooling Tower (3)	Open	3 x 4m^3	200 m^3/h	-	15 €/kW
Storage	Heat Storage	Water	2 x 100 m^3			300 €/ m^3
	Cold Storage	Water	2 x 100 m^3			300 €/ m^3
Network	District Heating (4)	Insulated Steel	2 x 0.12 m^2	250 m^3/h	9000 MW_h	200 €/m
	District Cooling (4)	Insulated Steel	2 x 0.33 m^2	400 m^3/h	3000 MW_c	350 €/m

In ParcBit power plant, the connection of the solar collectors has different configurations for summer/winter, allowing the collectors to provide heat to the absorption machine in summer or directly cover the heat demand in winter (Figure 9). The absorption and the screw electric chiller are cooled down by water and both use the same cooling towers, while the compression electric chiller is air cooled. The storage system comprises two cooling tanks and other two tanks for heating. The storage volume is very limited and hence it works more as energy buffer than storage.

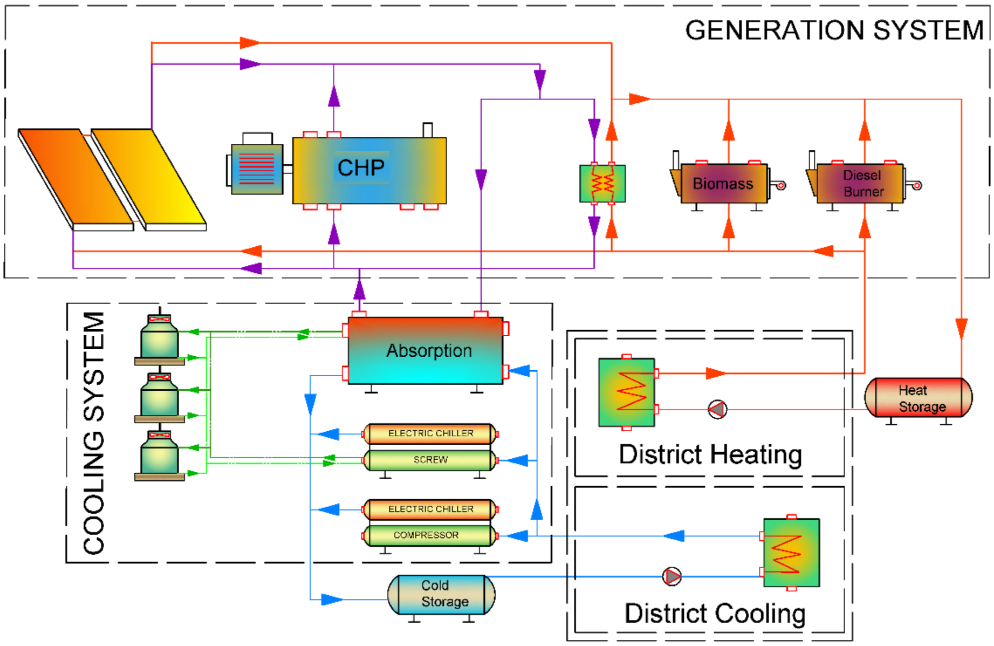


Figure 9: Parc Bit power plant hydraulic scheme.

In order to operate the power plant efficiently it is required to forecast accurately the solar generation from the field. To achieve such estimation for ST generation, it is needed to forecast the solar irradiation [79–81] and take into consideration the ageing of the solar collectors [82]. The forecast information can be used on a power plant simulator aiming to improve generation strategies, reduce generation expenses and maximize revenues in generation. The power plant simulator generates strategies by using a decision maker tool [83–85]. This tool supports the plant manager decision process while aims to optimize the cooling energy generation.

7. SOLAR COLLECTORS

Solar collectors connected to DH networks are mounted either on the ground or on buildings roofs, depending on availability and cost. These two possibilities are described in the following sections.

7.1. Ground-mounted collectors

When the collector area is large and the price of land cheap, the collectors are mounted on the ground, close to the heating plant, which makes the installation easy and economical. This type of solution is commonly adopted in Denmark, but also in Sweden and Austria. Ground-mounted collectors are arranged in rows of 10–25 modules in series [8], which are then connected in parallel. In order to maximize the efficiency of the array, its layout should be such that the outlet temperature of every row is the same. Uniform outlet temperatures are achieved when the flow rate in each row is approximately proportional to the row collector area. Collector rows having the same composition should be supplied by the same flow rate. Reaching uniform flow distribution in all operating conditions is unrealistic, so an amount of non-uniformity must be accepted. According to the German standard VDI 6002 [86] deviations within ±10% are acceptable. There are several methods to achieve good flow distribution. One is the adoption of a Tichelmann connection (Figure 10.b), which approximately equalizes the hydraulic resistances of the different rows, but also requires longer pipes and consequently additional cost. Alternatively, it is possible to install mechanical balancing valves (Figure 10.c), which are very effective, but entail higher cost and longer installation time. This is the most common solution adopted in large collector arrays in Denmark. Installing fewer collectors in rows which are farther away (and hence with higher hydraulic resistance) may be coherent with the concept that shorter rows should be supplied with lower flow rates (Figure 10.a). However, this approach requires very careful planning and precise calculation, as later adjustment would be very expensive. Finally, if the pressure drop across the collector rows is much higher than in the supply/return pipes, a sufficiently uniform flow distribution may be achieved without further action [87].

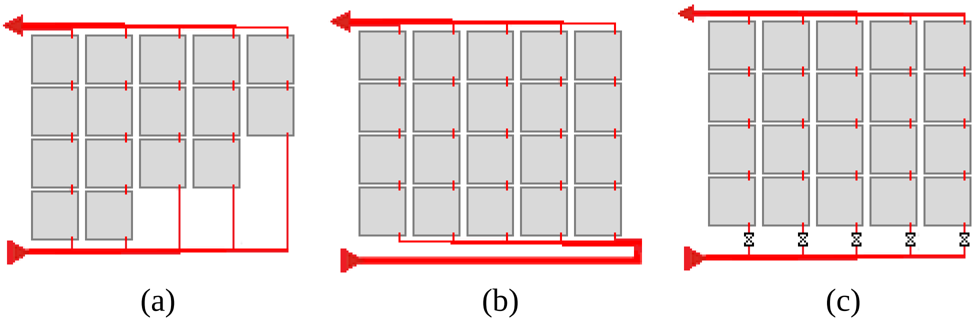


Figure 10: Possible array configurations to achieve uniform outlet temperature (adapted from [87]*).*

The European market of large solar heating systems is dominated by flat plate collectors [24]. These collectors have undergone a strong development during the last years with regard to quality, efficiency increase and cost reduction [82]. The collectors used in large solar installations have areas of 10-15 m^2, which make the installation faster and more cost-effective. Aluminium strips are commonly used as absorber, because they are easier to handle and cheaper than copper [19], but also steel and copper can be used. Given the large size of the collectors, several absorber pipes are connected in parallel, running from a supply to a return manifold, so to reduce the pressure loss. The collectors may have a polymer foil mounted between absorber and glass cover to decrease convection losses [88]. In some cases both collectors without and with foil are used, the former at the beginning of the row and the latter at the end, so to achieve the most cost-effective row composition [34].

More recently, collectors based on the heat pipe principle have also been proposed for DH applications, as in Vidailhan (France) in 2014 [89]. The collectors used in this installation are based on an aluminium roll bonded heat pipe, inserted in a double wall vacuum glass tube, in order to limit thermal losses and allow high efficiency, even at high operating temperatures. Efficiency between 60% and 70% are aimed at for temperatures between 80 °C and 110 °C [90]. Additionally, the dry thermal contact between the heat pipe condenser and the main pipe makes installation and maintenance fast and easy.

Depending on the climate, propylene glycol/water mixtures may be used as solar collector fluid to prevent freezing. Additives are also added to avoid corrosion [8]. As higher concentrations of glycol entail poorer fluid properties in terms of specific heat and heat transfer, a lower concentration assuring anti-freezing protection only to a certain extent may be preferred. If the fluid temperature approaches its freezing point, the pump of the solar collector loop starts and the fluid circulates, with or without the input of auxiliary heat.

The collector rows are connected in parallel through pre-insulated underground pipes like those used in DH networks. Unlike pipes for DH networks, the collector array pipes need to cope with higher and more frequent temperature variations. To deal with thermal expansion cycles of the pipes without risk of breakage, expansions fittings, such as expansion bellows or lyre loops, are installed. Wires for potential leak tracing can be embedded in the pipe insulation [8].

A control strategy using constant flow and a simple on/off controller is normally used in R/R configuration, where the solar heat is transferred to the return pipe of the DH network for preheating purposes. An auxiliary energy source is required downstream to reach the desired supply temperature for the DH network, even during most of the summer. Solar collector arrays built in Denmark between 1988 and 1996 used this control strategy [91]. “Matched flow” principle has become the dominant control method with collector array connected as an R/S system. Constant outlet temperature is achieved by regulating the flow rate based on the output of a simple collector array model with measured solar radiation, inlet fluid and air temperatures as inputs [91]. The collector array pump starts if one of the following conditions is met:

- the temperature at the outlet of the rows is higher than the temperature at the bottom of the buffer tank and/or the feed-in temperature to the DH network by a pre-set value;
- the energy output from the collector field calculated on the basis of measured inlet temperature and weather parameters is higher than a minimum pre-set value.

Due to its large heat capacity, the solar collector loop needs some time before reaching the desired outlet temperature. Hence, in the start-up phase, only the collector array pump is run. The pump on the DH side is turned on only when the temperature from the array is several degrees higher than the temperature on the DH side. If the solar irradiance is not high enough to reach the DH supply temperature, the water warmed up by the solar heat is mixed with hot water from the auxiliary boilers, which has a higher temperature than the DH requirements. The heat from the solar collector loop is transferred to the DH side loop through large flat plate heat exchangers. To maximize the heat transfer, the water flow rate on the DH side loop is such that an equal heat capacity rate on both sides of the heat exchanger is maintained [92]. The temperature difference across the heat exchanger is usually 3–6 K [8].

On a seasonal basis, the control strategy aims at supplying energy at the supply temperature of the DH in summer time (so that no auxiliary energy is required) and preheating the return of the DH in winter. The solar heat is transferred to the DH network whenever possible. If excess heat is produced, this is delivered to the storage. Typical operating temperatures of solar assisted DH networks are about 35 °C/80 °C [8] (see also Table 1).

7.2. Roof-mounted collectors

The general layout principles for roof-mounted collectors are the same as for ground-mounted collectors (Section 7.1). However, there are a number of practical issues, depending on how the collectors are mounted. The collectors can be mounted either with the same tilt and azimuth as the roof (i.e. integrated in or mounted on top of the roofing material), or using some kind of support. The second option is generally used for flat roofs or if the tilt and azimuth angles desired for the collectors differ from those of the roof. For collector arrays on flat roofs, the design principles are the same as for ground-mounted arrays (Section 7.1). For the first installation type, the roof tilt is often higher than ~15°, which makes access and safety requirements more difficult. This difficult access means that balancing valves are rarely used for ensuring balanced flow in the parallel rows. Collector rows and connecting pipes are designed so that the pressure drop in the rows is much higher than in the pipes. A resulting flow distribution within 10% of the average flow for all rows can be achieved in this way, so respecting the guidelines of the German standard VDI 6002 [86]. The Tichelmann connection (Figure 10.b) is rare, due to the extra cost. Especially in roof-integrated/mounted collectors, it is important to consider the thermal expansion of the components and design the array, so that the mounting system allows the necessary movement. Flexible pipes between collectors can be used for the same reason.

Difficult access also makes deaeration of the collector loop more problematic. Air in the collector loop can lead to incorrect control of the pump, for example due to air pockets accumulating near the temperature sensor at the top of the collector. Finally, the pressure in the collector loop has to be carefully adapted to the height of the collectors with respect to the lowest point of the loop, to avoid boiling or under-pressure in the loop [93].

Another important aspect for roof-mounted collectors is the aesthetics. These installations are normally visible from other buildings or from the surroundings, so they should harmonize with the rest of the building.

As the roof area of a single building is limited, the complete collector array may be distributed on several buildings. Thus, an important design consideration is whether to connect several of these collector fields together to a common connection to the DH network, or to connect them individually.

8. STORAGE

Without storage, the potential solar fraction of a SDH system is very limited due to the limited synchronicity between solar radiation and heat load. Thus, storage is required to bridge the mismatch between the two. Short term storage, normally in the form of steel tank(s), makes it possible to increase the solar fraction of the system up to 15–20% [8,46]. It can also be used by the auxiliary energy system, being charged in periods of lower demand and discharged to cover peak demand (e.g. in the early morning). As an advantage, the required power of the auxiliary energy system is lower. Higher solar fractions (up to 90%) are proven to be achievable through a seasonal thermal storage [50]. The storage is charged in summer, when excess solar heat is produced, and discharged whenever it is hotter than the operation temperature of the DH network and the collectors do not produce enough heat. For diurnal storage of solar heat, 50-100 litres water equivalent per square meter of collector area are normally used. For seasonal storage with 90% solar fraction, around 3500-4000 l/m^2 are needed [8,50].

Four main types of seasonal storages are currently used: tanks, pits, boreholes and aquifers [94]. However, aquifer storage has mainly been used for heat pump/cooling systems. Both tanks and pit storages can also be used for diurnal storage, while aquifers and boreholes cannot. The choice of storage technology depends on the size of the store, the required heating power, the geological situation and whether the storage is for diurnal or seasonal use [94]. Ellehauge and Pedersen [95] analysed the different storage types and give guidelines on the system integration. As stated in Section 2.3, stores are either located at the main heating plant, or distributed along the DH network. In the existing systems, all the seasonal storages are located centrally, while the distributed storages are nearly always tanks of small volume.

Water tank: Water tanks are most versatile, as they do not require special geological conditions. They are made of steel or concrete walls with steel liner welded on the inner side to assure water and vapour tightness. Tanks are generally well insulated. Having a high height-to-diameter ratio compared to water pits, tanks achieve better stratification, but they are usually smaller for economic reasons, with volumes up to 12,000 m^3 [96]. Thermal stratification is enhanced by multiple inlets/outlets placed at different heights, which allow charging/discharging the tank at the right temperature level.

Water pit storages: This technology seems to be the most cost-effective when very large heat capacities are needed. Recently pits with a volume up 200,000 m^3 have been built [97]. The present state-of-the-art of this technology comes from experiences made in Denmark in the last years [98–100]. A water pit is conceptually similar to a water tank, but differs in terms of construction, materials and size. Water pits are excavated in the ground and made watertight by welding polymer sheets on the sides and the bottom, without insulation. Due to the large top area, the lid (which also include thick insulation) is not supported, but floats directly on the water. This component is the most critical, both from the construction and economic point of view [95,99,101].

Gravel-water pits: If a pit storage is filled with gravel and water instead of water, the lid construction is simpler, as it can be laid on the gravel. On the other hand, gravel-water stores require a very careful installation, as later maintenance is not possible. They also require larger volumes than water pits, due to the lower heat capacity [11,96,102].

Boreholes: Borehole storages are made by drilling deep vertical holes in the earth/bedrock and filling them with pipe heat exchangers and thermally enhanced grouting material. To reduce thermal losses from the top, an insulation layer and a watertight foil cover the top of the store. As the sides of the store are not insulated, the storage is charged so that the centre is at a higher temperature that the surrounding. This is achieved by connecting the borehole heat exchangers in series from the centre outward. Borehole stores can be easily expanded, adding new holes and pipes at the edges of the existing ones. A drawback is the need for a buffer tank for short term storage due to poor heat exchange capacity rate between pipes and soil [46,50,103–105]. Many borehole storages are used together with a heat pump (Section 3.1), so that the storage temperature and thus the heat losses are lower. However, two seasonal borehole storages have been built with relatively high storage temperatures, one in Sweden [106] and one in Canada [50].

Aquifer: In aquifer storages, underground water is extracted from a cold well, heated up and pumped back into the store through a hot well [107,108]. This technology is probably the cheapest, but requires very specific hydrogeological conditions, such as water-saturated soil and very little ground water movement. Additionally, permission from water authorities is normally necessary. An example of aquifer storage is located in Rostock [46].

9. DISCUSSION

9.1. Ownership and economy

Different types of ownership and financing of SDH systems are found in Europe. Large centralized collector fields in Denmark are typically owned and operated by the owner of the DH network, which can be either a public utility or a private cooperative [109]. This represents the least complicated solution, as it requires neither contracts nor feed-in tariffs with third parties. A loan guarantee is usually given by the local municipality, which has almost no risk in doing so, as consumers are bound to a contract obliging them to be customers of the DH utility. The income for the DH utility is then secured and used to pay back the loan [110]. With this guarantee and stable economic boundary conditions, low interest rates can be obtained, resulting in a lower levelized cost of heat supplied by the collector field.

With decentralized feed-in systems owned by parties other than the DH operator, the feed-in tariff has to be agreed with the DH operator who will also define the technical conditions that the system needs to fulfil in order to be allowed to connect and feed in to the DH network. Roof-mounted collector fields can be legally more complicated. The most common solution is that the owner of the building also owns the collectors and sells/buys heat from the DH network according to a contract, like in recent decentralized plants in Sweden [110]. However, there are some cases, for example in Germany, where the utility owns the collectors, mounted on a privately owned building. This kind of combination is possible, but needs to be carefully regulated with an agreement between the two parts to define the respective responsibilities and liabilities [110].

Another possibility is that an ESCo installs and operates the collector field and then sells the solar heat to the DH network or to the building owner (if the collectors are roof-mounted) [111,112]. The ESCo takes the financial risk away from the DH company or the building owner, who only needs to pay according to amount of heat delivered. This solution has been proven to be successful, as utilities and building owners without experience in ST systems may not be willing to accept the risk of the investment, even if the long-term economic feasibility is advantageous. For example, in Austria the company Solid has installed large decentralized solar plants in the town of Graz and most of these are now operated in the form of an ESCo [113].

Although less common, another solution is a co-operative ownership, where the collector array is split and owned by different private people, who receive a yearly dividend. An example is the 454 m^2 collector field in Neckarsulm, Germany [110].

In Figure 11 systems are compared as well in terms of Levelised Cost Of Heat (LCOH) based on the results of [114]. The comparison is between solar block heating (SBH) systems roof mounted and solar district heating (SDH) ground mounted, comparing at the same time seasonal storage (SS) and diurnal storage (DS). As the LCOH has a dependency on the climate and local conditions, LCOH is shown for both southern european and central-north european regions. The lowest LCOH is given in southern european regions, ground mounted solar distric heating and diurnal storage.

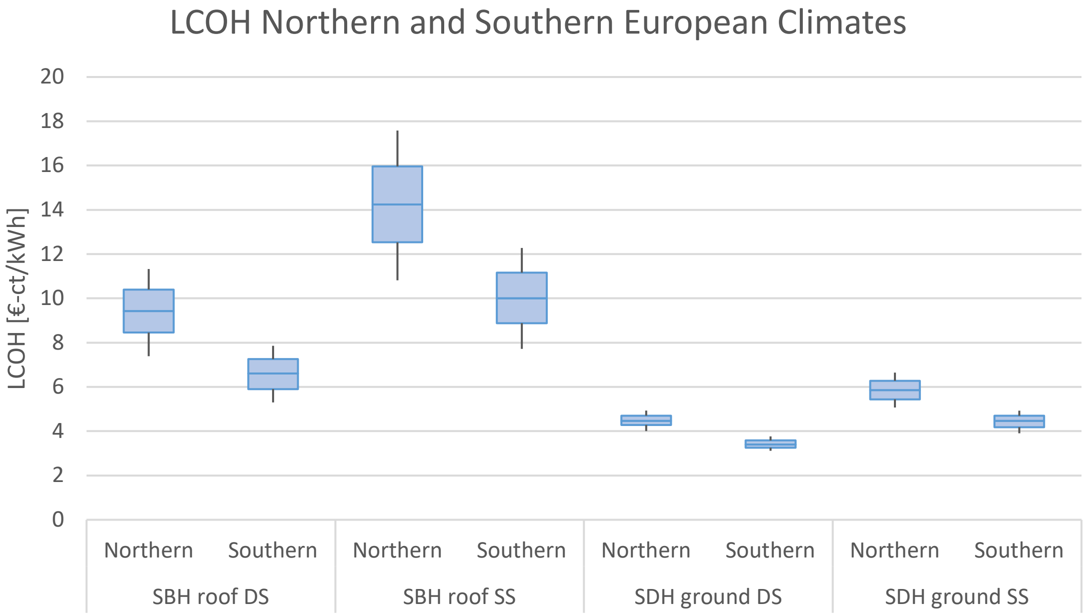


Figure 11: Levelised Cost Of Heat in Northern and Southern European Climates

9.2. **Trends**

In Denmark, the development of large solar collector fields for DH applications has been remarkable in the last years (Figure 12). In 2015, the current largest solar collector field was installed in Vojens, with a collector area of 70,000 m^2 and a seasonal water pit storage of 200,000 m^3 [24]. This trend is expected to continue in the coming years (Figure 12). In 2016 a 150,000 m^2 solar collector field is expected to be completed in Silkeborg [115]. Compared to the period 2014-2016, a milder increase in the installed collector area is expected for 2017, due to some changes in the relevant regulations in Denmark. Solar collector fields connected to DH networks put in operation by the end of 2016 could take part in a trade of *energy-saving points* [116]. This market is similar to carbon emissions trading. Companies reaching their energy saving targets can sell their extra energy-saving points to companies that do not meet their energy saving requirements [117]. The price of these energy savings is not fixed, but depends on the market supply and demand. In the period 2012-2014 the average market price was around 0.04-0.05 €/kWh [118]. The current agreement which allows SDH to be part of this market expires at the end of 2016 and a new one has not yet been set for the coming years. Many DH companies have suspended their plans for solar installations, waiting to see how the situation would evolve, resulting in a slow-down in the expansion of the market as predicted for 2017 (see Figure 12). This shows the sensitivity of the major SDH market to changes in political instruments.

The Danish experience proves that large centralized solar collector fields for DH are a well-established technology and DH utilities do not refrain from commissioning increasingly larger installations. At the same time, it also shows how political decision and economic conditions may play an important role in the spread of well-established technologies in the field of renewable energies.

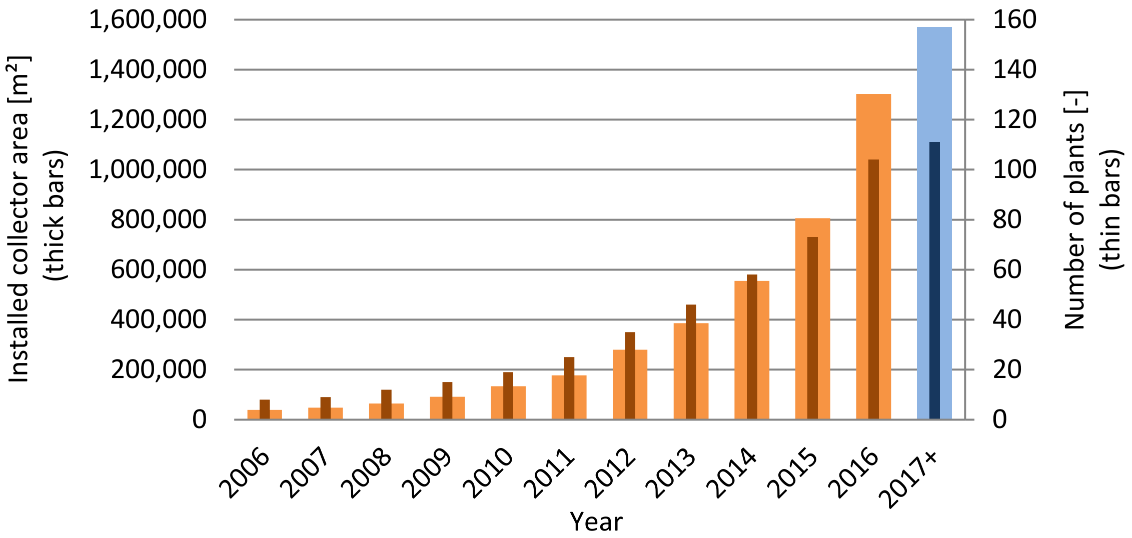


Figure 12: Solar district heating in Denmark: installed collector area and number of operating (orange) and upcoming (blue) plants at the end of 2016 [119].

Due to economies of scale, large ground-mounted collector fields are usually characterized by the lowest specific cost, compared to other ST systems. Additionally, enhancements in the production and installation have progressively decreased the investment cost of these systems in the last years, with current prices ranging between 200 € and 300 € per square meter of collector. Figure 13 shows the trend in investment cost per unit area of collector for large solar collector fields in Denmark in the last 15 years. A remarkable cost reduction has been achieved especially in fields equipped with seasonal storage, due to the improved know-how and to the larger storage volume, which decreases the specific cost.

Likewise in solar roof-mounted systems the learning curve and cost reduction of the solar collectors has lowered the specific cost in recent years. Currently the price per square meter ranges between 500€ and 1000€ depending on the installed area [114]. However the largest registered roof-mounted system cost twice as much as a ground mounted system of the same size.

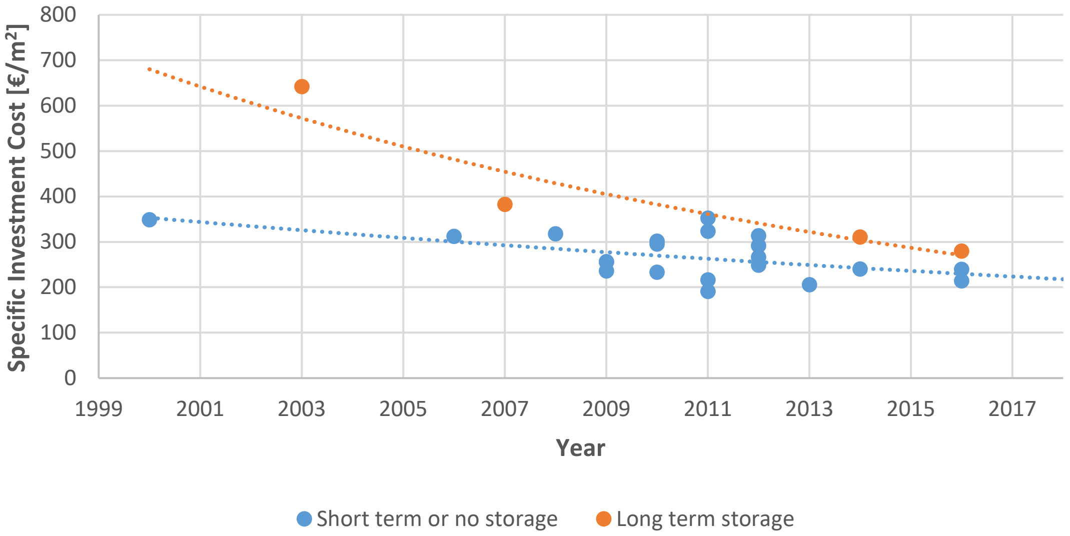


Figure 13: Trend of investment cost per unit area of collector of large centralized systems in Denmark in the last 15 years [114,120].

In the same way due to economies of scale, large thermal storage have usually a low specific cost. In [114] the specific cost of non-pressurised tanks, boreholes and pit thermal storages are presented and compared. The authors derive cost functions for the different thermal storages in terms of the stored volume and show that pit thermal storages have lowest costs.

9.3. System Advantages and Disadvantages

Four different types of solar district heating and cooling have been presented in this work. In Table 5 the main advantages and disadvantages are shown seeking for comparison.

Table 5. Advantages and Disadvantages of the studied systems

System	Advantages	Disadvantages and Limitations
Central Solar	Specific cost of solar collectors and stores is lower due to economy of scale	Higher transmission losses due distance to end user
	Faster installation of solar collector field due to easy accessibility with ground mounted collectors	LCOH of competing heat sources are also lower due to economies of scale and possibility of CHP
	Possibility of integrating large thermal storage to increase the solar fraction of the system	High supply temperatures reduce and limit solar collectors performance and annual yield
Solar Block	Possibility to integrate solar heating system into distribution network and buildings	Difficult accessibility for installation or maintenance
	High energy harnessing due proximity of the user to generation	Lower density of customers usually entails higher specific investment costs and thermal losses as most systems have buildings with relatively low energy demand
	No extra land cost to install solar collector field	Extra complexity to the overall design process of a new building area

Solar Feed-in	Usage of existing infrastructure: Roof tops and DH network High energy harnessing due proximity of the user to generation Possibility of pre-fabricated systems	Difficult accessibility for installation and maintenance Feed-in contract needs to be established with DH operator and risk of low feed-in tariffs
Solar Cooling	Solar availability matches cooling demand Solar heat can be used for both heating and providing cooling via an absorption chiller	Absorption chiller requires high heating temperatures which reduces solar yield and limits power plant operation temperature Absorption chiller will be required if not already included in the system design

10. CONCLUSION

Based on the comprehensive literature review and study cases proposed, the conclusion can be summarized as follows:

- Large scale centralised solar thermal plants for district heating are now fully commercially viable given the right financial boundary conditions, as is the case in Denmark. This has led to a vibrant market, large cost reductions and improvements in field control.
- These systems all have ground mounted collectors, which lead to lower costs than for roof mounted collectors due to the possibility of using larger collectors and a more rational and simpler mounting as well as several other practical issues.
- System integration is very dependent on the individual district heating/cooling network, while the collector field itself is more dependent on ground or roof mounting. Many different configurations can be found in the literature, and no common system design has yet been established. This is especially true for systems with roof mounted collectors, where the collector fields are often distributed on several buildings.
- Seasonal storage costs have decreased significantly in recent years, and there is a trend to use pit storages for this purpose. However, diurnal storage is still dominant in all systems, especially in block heating systems.
- Centralized systems with ground mounted collectors together with seasonal storage have a lower levelized cost of heat than block heating systems with roof mounted collectors and diurnal storage.
- Decentralized, feed-in systems, have become more common but are still not fully commercial and the literature shows that there is not yet a standard design for such installations, with different connection configurations used in different cases.
- Despite the theoretical advantages of solar district cooling, there are very few studies and existing plants g. Most larger solar cooling systems are restricted to a single customer and thus are not district cooling.

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