INTEGRATING CONCENTRATED SOLAR THERMAL IN DISTRICT HEATING - A SIMULATION STUDY IN TRNSYS

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Abstract

Since concentrated solar collectors can deliver higher flow temperatures with higher efficiency compared to standard collectors such as high performance flat plate (HPFPC) and evacuated tube collectors, they are of interest for heating networks with supply temperatures above 100 °C. In addition, they can usually track the sun, which can increase the solar yield over the course of a day.

In this paper, different collector technologies and their properties are described. In addition, concentrated and non concentrated collectors are compared with each other on the basis of their Solar Keymark characteristics and in a simulation study for implementing in district heating systems.

The comparison and simulation of high performance flat plate collectors and parabolic trough collectors for heating networks shows that at higher network temperatures, parabolic trough collectors deliver higher yields at German locations. The parabolic trough collectors (PTC) investigated are especially interesting at locations with high direct radiation, as this can be better reflected and converted into heat than diffuse radiation.

This work is part of the German research project Pro-Sol-Netz, funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK). Pro-Sol-Netz aims to develop and evaluate technologies for the integration of parabolic trough collectors in district heating (DH) and process heat.

Keywords: concentrated solar thermal collectors, parabolic trough, collector technologies, district heating, TRNSYS, simulation study

1. Introduction

Solar thermal collectors are one important technology for the supply of renewable heat in DH and for industrial processes. Among other things, they can be integrated in DH and installed decentrally on detached houses and apartment buildings or industrial buildings (Mazhar et al. 2018). There is a great potential for solar thermal in DH in Germany, because around 14 % of homes were heated with district heating in 2019 (AGFW, 2022). Large-scale high performance flat plate collectors and evacuated tube collectors without and with CPC (compound parabolic concentrator) are the state of the art for the integration of solar heat into DH networks with supply temperatures up to 90 °C. These standard collector technologies are described e.g. in the AGFW's 'Solar thermal practice guide' (AGFW, 2021). However, existing heating networks, heating networks with large customers and industrial plants often require high transportation capacities or high temperatures respectively. In these cases, it can be important to be able to provide temperatures of around 100 to 140 °C economically using solar thermal energy (Agora Energiewende, 2019).

Other collector technologies, such as parabolic troughs (Figure 1) and Fresnel collectors, can provide supply temperatures above 100 °C with higher efficiency compared to standard collectors, therefore they are of interest for the decarbonization of existing DH networks. These collector technologies are new for utilities and other stakeholders in district heating.

Therefore, an analysis and comparison of collector technologies from various manufacturers is an important step towards encouraging the integration of solar thermal energy in heating networks. In this paper, the comparison of different solar thermal collector technologies is shown. In addition, a simulation case study comparing parabolic trough collectors and flat plate collectors in a DH network was carried out.

10.18086/eurosun.2024.03.05 Available at http://proceedings.ises.org

Figure 1 Photo of parabolic trough collectors (Solarthemen Media GmbH, 2021)

2. Collector technologies

Different collector technologies have various characteristics and specific features. Concentrated collectors are designed to focus the direct radiation of the sun onto a secondary absorber element, which considerably enhances the solar yield at high temperatures. Examples include evacuated tubes with CPC, parabolic troughs, and Fresnel collectors. In comparison to standard collectors such as flat plate collectors, evacuated tube collectors with and without CPC, which typically have a fixed collector slope angle, there are also collectors with tracking systems. Tracking systems allow the collectors to follow the sun, minimizing the angle of incidence and thereby maximizing the amount of irradiation received on the collector surface and the collector output. Tracking systems can be classified into single-axis and dual-axis types. To avoid damage from overheating, collectors can be tracked away from the sun, allowing for better regulation of thermal yield (Stahlhut et al. 1-2/2022).

Various heat transfer fluids are used in solar collectors based on the specific technology and application, as typically specified by the manufacturer. The most prevalent fluids include water, water-propylene glycol mixtures, thermal oil, and steam. When using water, the costs are generally low, and transferring from the solar circuit to a secondary circuit may not be necessary. However, a strategy to prevent freezing under any condition is essential. Water can be used for operating temperatures up to around 200 °C, but systems with temperatures exceeding 95 °C must be pressurized, which incurs additional costs. Alternatively, using water-propylene glycol mixtures can prevent freezing. These fluids can handle operating temperatures up to approximately 170 °C for short durations and up to 120 °C for extended periods (TYFOROP Chemie GmbH, 2015). Thermal oils are suitable for use at temperatures up to 400 °C, but some of these oils have a high viscosity at low temperatures. This can cause issues when starting a cold system. The environmental impact of high-temperature oils should also be considered (Therminol, 2022).

2.1. Flat plate collector

Flat plate collectors are typically utilized for low and medium temperature applications below 90 °C. As illustrated in Figure 2, these collectors have a large absorber surface, making diffuse radiation a significant factor in their heat yield. This feature allows flat plate collectors to generate heat effectively in cloudy, dusty, or humid conditions. They are generally constructed with a glass cover, copper tubes, absorber plates, thermal insulation, and an aluminum casing, which makes them relatively inexpensive to produce (Shamsul Azha, et al. 2020). To enhance performance, many manufacturers of high performance collectors use anti-reflective glass. Flat plate collectors can have either single or double glazing. Double-glazed collectors perform better at higher temperatures due to reduced heat loss, but they are more costly and heavier than single-glazed versions.

These double-glazed large-scale collectors are often used in DH applications.

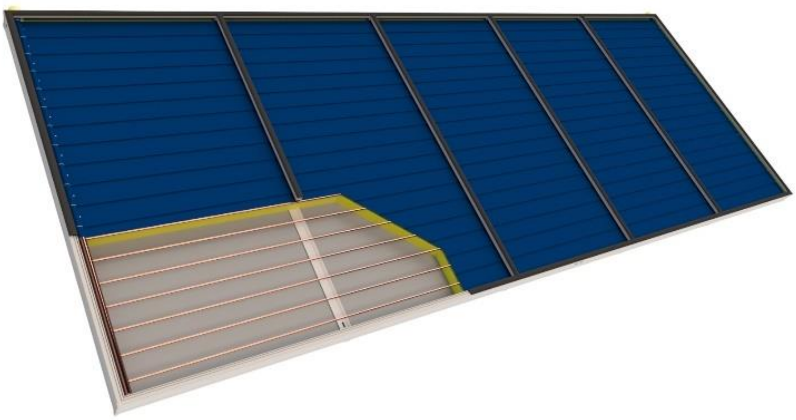

Figure 2 Structure of a flat plate collector for district heating (GREENoneTEC)

2.2. Evacuated tube collector without and with CPC

There are two main types of evacuated tube collectors: Sydney tube collectors and single glass tube collectors. Sydney tube collectors consist of double glass tubes with an inner absorber tube coated with a selective material, and the space between the tubes is evacuated. Single glass tube collectors consist of one evacuated tube with a conventional metallic absorber inside. The vacuum insulation in both types reduces heat loss and enhances performance at higher collector temperatures. An example of an evacuated tube collector with heat pipes is shown in Figure 3. It uses a trapezoidal plate with a high reflection factor, mainly reflecting diffuse radiation onto the vacuum tube.

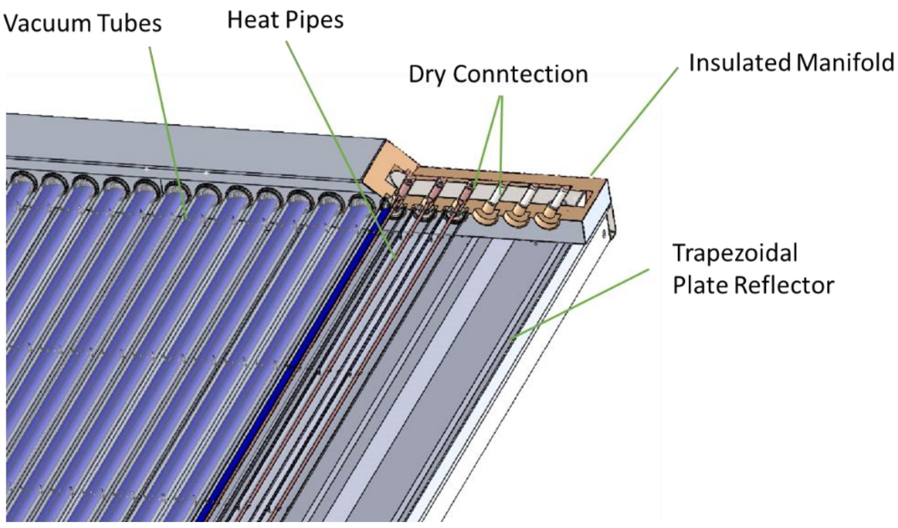

Figure 3 Main components of an evacuated tube collector without CPC (AKOTEC)

A specific design of this technology is the evacuated tube collector with CPC, which includes a parabolic mirror on the backside of the absorber tube (see Figure 4). This mirror geometry reflects direct radiation onto the absorber tube at any angle of incidence, eliminating the need for tracking and allowing for small row spacing due to minimal shading and the flat geometry. This design is highly area-efficient and can economically generate high temperatures (manufacturer information).

Figure 4 Main components of an evacuated tube collector with CPC, sectional view (Ritter Energie- und Umwelttechnik GmbH & Co. KG)

2.3. Parabolic trough collector

This technology features a large, curved mirror that focuses incoming radiation onto the absorber tube (see Figure 5). An electric servo motor can be used to adjust the angle of incidence in order to optimize solar radiation onto the collector plane during the day. Due to their large size, these collectors are typically tracked on a single-axis. A significant advantage of this design is comparatively low heat losses because of the small surface area of the absorber tube. Consequently, high temperatures exceeding 400 °C can be achieved efficiently through the concentration of direct irradiation. However, parabolic trough collectors are generally not stagnation safe, meaning that overheating protection is mandatory. Stagnation is typically prevented by rotating the collector out of direct sunlight. Most absorber tubes are enclosed by a protective glass tube, and many receiver tubes are vacuum-insulated, which can be re-evacuated during maintenance (W. Weiss, M. Rommel, 2008).

Figure 5 illustrates the schematic structure of a large parabolic trough collector, highlighting the key components and geometric parameters.

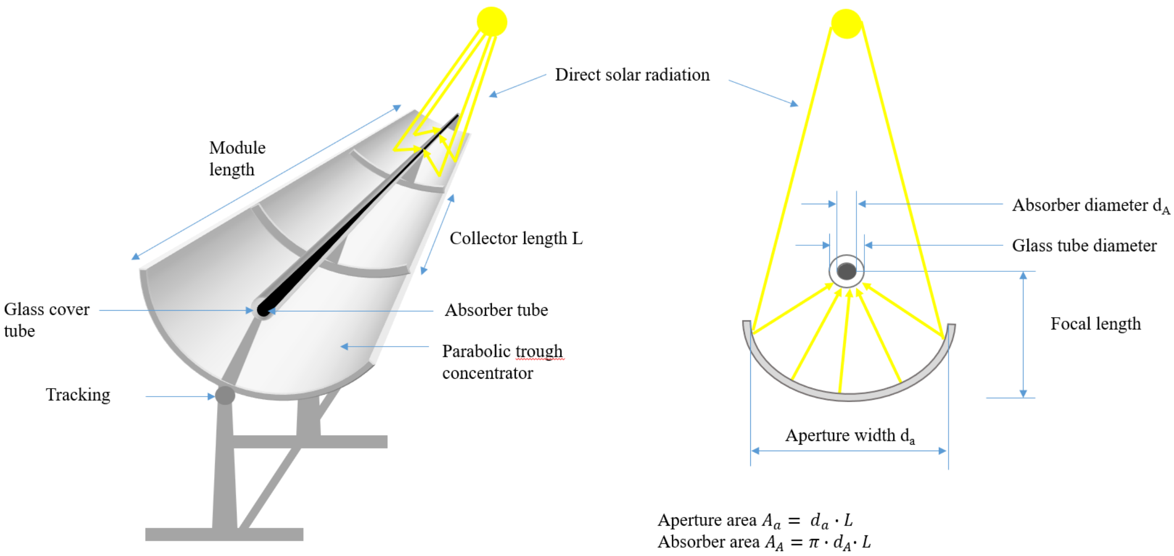

Figure 5 Large parabolic trough collector, perspective view and cross-sectional view (figure: Solites)

2.4. Fresnel lenses collector

The Fresnel lenses by a Danish manufacturer represents an innovative concentrated collector technology. This design focuses direct radiation onto the absorber surface behind the lenses, see Figure 6. Each module contains eight plastic lenses that act like magnifying glasses to concentrate light. Its compact design allows for two-axis tracking, which significantly increases solar yield. Additionally, there is no risk of glare, as the collector consistently reflects towards the sun due to the dual-axis tracking (datasheet, manufacturer information).

Figure 6 Photo of Fresnel lenses, Heliac in Denmark (Jensen et al. 2022)

3. Comparison of solar thermal collectors according to Solar Keymark

Most funding programs for collectors require that the collectors are certified, to have standardized performance parameters available. The most widely used certificate in Europe is the Solar Keymark certificate, which is also accepted in many countries outside Europe. Accredited test laboratories evaluate collectors according to the EN 12975 and EN ISO 9806 standards. The certification process also includes periodic monitoring of the manufacturing process and the product. Large parabolic trough collectors are hard to test in laboratories due to their size, but in-situ testing is a valid option under the Solar Keymark certification scheme (Solar Keymark, 2024).

Concentrated solar collectors focus the solar radiation onto a secondary element, from which the converted heat is extracted and, if necessary, converted again. In case of a parabolic trough collectors the radiation is directed and focused from the mirrors to the absorber tube. Compared to standard collectors such as flat plate collectors and evacuated tubes, the influence of diffuse radiation on parabolic trough collectors is low. This is due to the comparatively small surface area of the absorber (Weiss and Rommel, 2008).

The next Figure 7 shows the specific annual yields of three parabolic trough collectors with gross areas of 6 to 15 m² and a standard high performance flat plate collector according to their Solar Keymark certificate as a function of the average collector temperature. The mean temperature corresponds to the mean value of the supply and return temperatures of the collector. Solar Keymark provides specific annual yields for operating temperatures of 25 °C, 50 °C, and 75 °C at reference locations in Athens, Davos, Stockholm, and Würzburg. The following diagram shows values for Würzburg, Germany. Besides the standard temperatures, an additional operating temperature of 100 °C was calculated using the ScenoCalc tool, which is used to calculate the values for Solar Keymark certificates (ScenoCalc, 2024).

From collector mean temperatures above 55 °C, there is a yield advantage for concentrated collectors. The drop in specific yield at higher temperatures is not as steep as for the HPFPC. In this comparison concentrated collectors are therefore more suitable for high temperature applications.

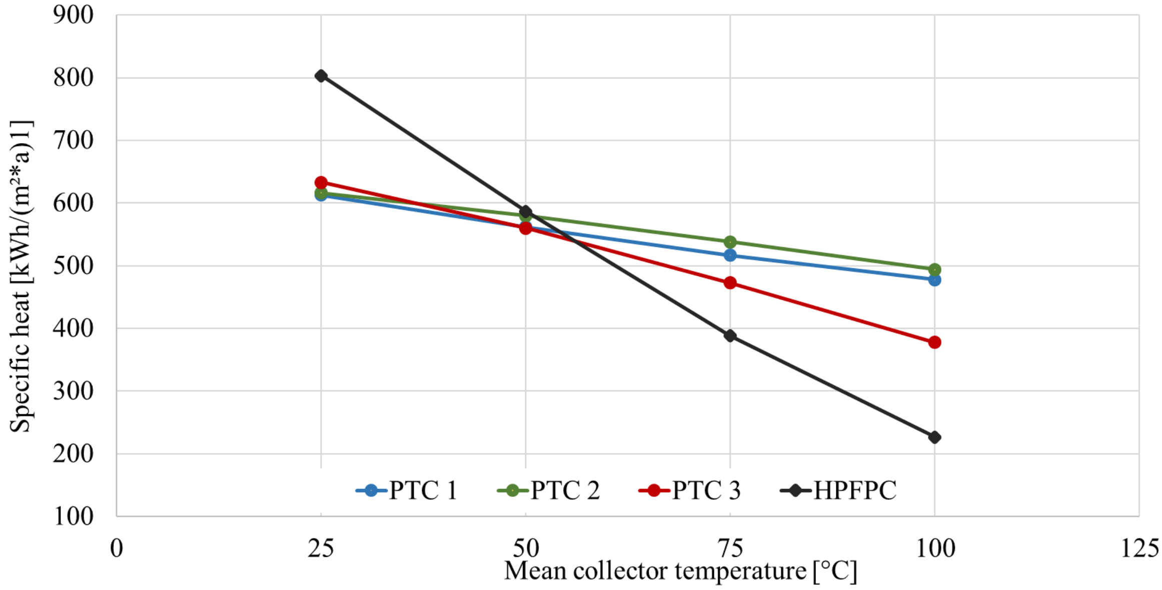

Figure 7 Specific annual heat yield of different small parabolic trough collectors (PTC) and a high performance flat plate Collector (HPFPC), related to the gross area, location Würzburg (Solar-Keymark) (ScenoCalc) (figure: Solites)

All preceding analyses and references are part of the report RA1 in IEA SHC Task 68, which will soon be available at (Task 68, 2024). Within this report, further collector technologies are analyzed Subsequent sections are based on additional investigations.

4. Case study

4.1 Parameterization

In a TRNSYS simulation case study, a heating network with supply temperatures of 140 °C in winter and 120 °C in summer and an annual heat demand of 6,150 MWh is fed by 2,250 m² aperture area of the PTC 1800 parabolic trough collector from the manufacturer Soliterm. There is also a buffer storage tank with 1,000 m³. Frankfurt am Main, Germany, is the reference location for the weather data used. The tracking axis is north-south, i.e. the collector tracks the sun from east to west. In addition, a stagnation prevention control is installed, which turns the collector out of the sun if the collector temperature is too high. The remaining heat requirement is covered by an additional heater. The results are compared with a high performance flat plate collector for solar district heating applications simulated in the same system. The main parameters of the case study are listed in Tab. 1 (TRNSYS, 2024)

Tab. 1 Parameterization of the case study

Parameter	Description
TRNSYS type / technology	Type 1357 / parabolic trough collector
Collector model, manufacturer	PTC 1800, Soliterm
Aperture area	2,250 m²
Row distance	4 m
Storage volume	1,000 m³
Maximum storage temperature	150 °C
Supply/return temperatures summer	120/70 °C
Supply/return temperatures winter	140/65 °C
Reference location	Frankfurt am Main, TRY 2015 (test reference year)
Source weather data	DWD (Deutscher Wetterdienst, German Weather Service)
Annual load	6,150 MWh/a
Feed in type	return-supply
Storage mode	Operation with charging to required supply temperature
Tracking	single-axis, north-south axis, tracking away when supply temperature of collector is 153 °C
Simulation period	1 year
Simulation time step	1 hour

4.1 Main results

The solar fraction of the parabolic trough is almost 20 %. Therefore, it generates almost 1,200 MWh heat per year while the high performance flat plate collector achieves less than 10 % solar coverage and 600 MWh per year heat. The specific solar yield shows the difference between the two technologies. The parabolic trough collector achieves 526 kWh/m² per year and the high performance flat plate collector 276 kWh/m² per year. The simulation results show that the parabolic trough collector can achieve supply temperatures of over 100 °C. The flat plate collector, on the other hand, produces significantly lower heat yields in this application. Tab. 2 gives an overview of the main results of the simulation study for both collector technologies. The solar yields of the PTC 1800 parabolic trough collector are at a high level from March to September inclusive. However, the yields in winter are not sufficient to supply the heating network, even on sunny days. Nevertheless, they are many times higher than the yields of the high performance flat plate collector. Proportionally higher heat losses from the storage tank are to be expected using the concentrated collector due to higher supply and storage temperatures. The pumps are switched on more often because more heat is supplied by the parabolic trough collector.

Tab. 2 Main results of the case study, comparison of parabolic trough and high performance flat plate collector

Output	Parabolic trough collector	Flat plate collector
Annual solar yield	1,157 MWh/a	600 MWh/a
Specific solar yield	526 kWh/(m²*a)	276 kWh/(m²*a)
Solar fraction	18.8%	9.8%
Number of pump switch-ons for the collector circuit	337	286
Number of pump switch-ons for the solar circuit	320	267
Number of stagnation days	5	0

4.2 Monthly solar yields

Figure 8 shows the monthly heat demand (Load) and the solar heat yield supplied by the parabolic trough collector (Solar). The remaining heat is supplied by an auxiliary heater (Aux). As there is more irradiation and a comparatively low heat demand in summer, the solar fraction is comparatively high from March to September. Due to the solar fraction of 100 % in July and August and 5 stagnation days, the collector area and buffer storage could be further optimized in their size.

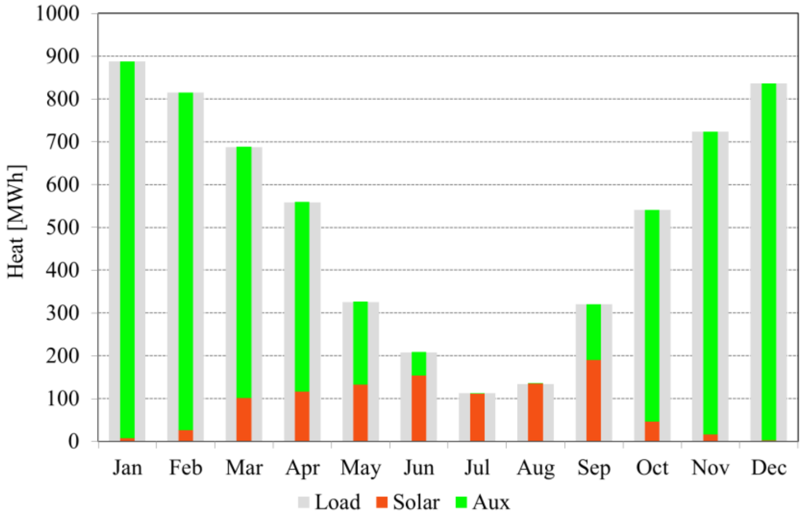

Figure 8 Monthly solar yield, parabolic trough collector

4.3 Temperature and radiation evaluation on a typical sunny day

The evaluation of day-dependent simulation results is an important measure for comparing the parabolic trough collector with the high performance flat plate collector. Based on the radiation data, identical days are selected and uniform diagrams are generated from the results, which are comparable for the respective day. A daily diagram is generated for both collectors, with simulation results provided at hourly intervals. Figure 9 illustrates the radiation values entering the collector level, represented by dashed lines. The horizontal axis indicates the time of day.

An example of this daily evaluation is shown in Figure 9, which presents the daily diagram of the parabolic trough and the HPFPC for 02. July, covering the period from 4 a.m. to 10 p.m. The high proportion of direct radiation at the collector level indicates a sunny day. The direct radiation in the collector plane of the PTC has a m-shaped curve. This is due to the single-axis tracking in east-west direction The parabolic trough collector is therefore able to deliver relatively constant solar yields over a longer period of the day. Constant energy yields throughout the day make it easier to control the pumps in the collector and solar circuit, as load demand is usually low at midday (12 am to 2 pm) and comparatively high in the morning and afternoon. In comparison to that, the direct radiation at the collector level of the HPFPC looks like a downwards facing parabola and is highest at midday (12 pm to 1 pm). This is due to the fixed collector slope which is 15°. At midday the direct radiation at the collector level of the HPFPC is higher than the direct radiation at PTC level. As the diffuse radiation for the HPFPC has an influence on heat generation, it is shown here.

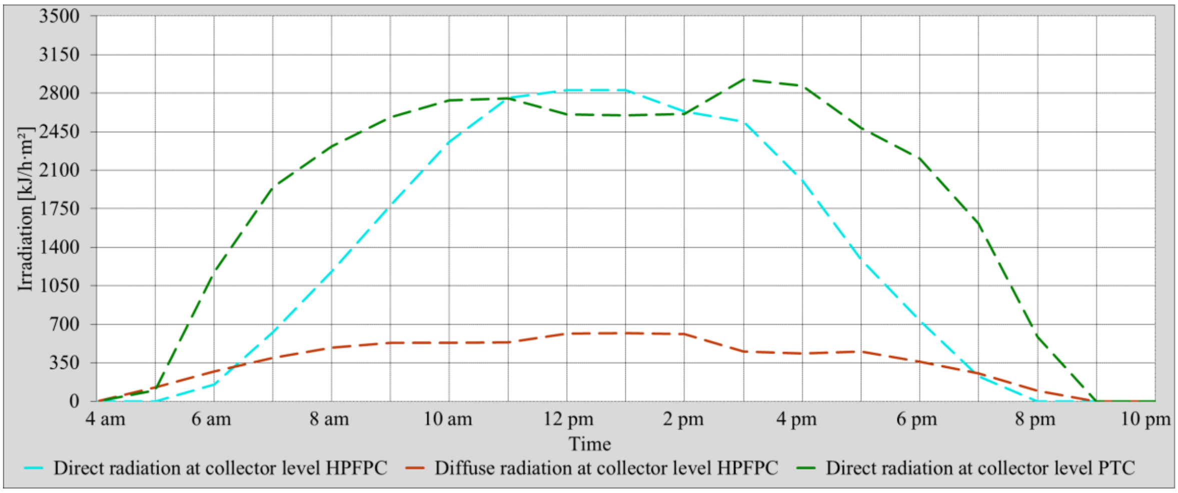

Figure 9 Daily diagram, 02. July, sunny day, parabolic trough collector (PTC) and high performance flat plate collector (HPFPC), relevant irradiation for heat generation

The following Figure 10 shows values that relate only to the parabolic trough collector on 02. July. The supply and return temperature (T_supply, T_return) of the PTC refer to the secondary vertical axis and are shown with solid lines. The scale of the radiation values can be seen, as in Figure 9 on the first vertical axis, which are shown with dashed lines. The total, direct and diffuse radiation entering the collector level are shown. In addition, the total horizontal radiation is shown in yellow. As previously mentioned, the irradiation in the collector plane has a m-shaped curve. This enables the PTC to supply constant temperatures to the DH system throughout the day. Due to transmission and storage losses, the collector delivers nearly 140 °C, even though the required supply temperature is 120 °C.

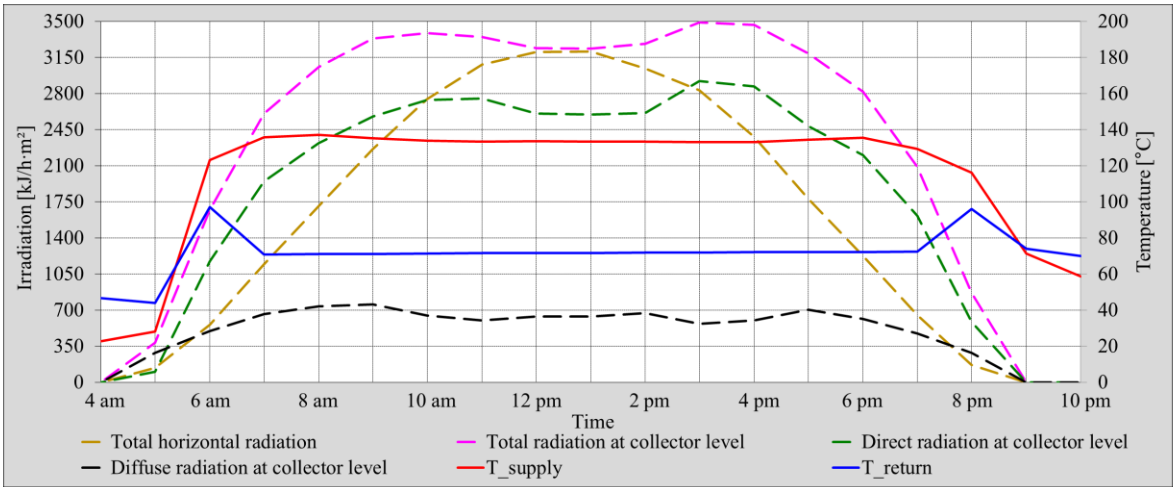

Figure 10 Daily diagram, 02. July, sunny day, parabolic trough collector, solid lines: temperatures, dotted lines: irradiation

4.4 Conclusion of the case study

On cloudy days, the solar yields of parabolic trough collectors are significantly lower than those of flat plate collectors as the parabolic trough has a comparatively small absorber surface, which is relevant for the yields from diffuse radiation. In the case study, the parabolic trough collector has a clear advantage overall. Due to the required heating network temperature of up to 140 °C, the flat plate collector is not able to supply heat efficiently.

A decisive advantage of parabolic trough collectors is the increased and adjustable solar yield due to tracking. The daily evaluations show that on sunny days, the direct radiation at the PTC level is relatively constant and there is no peak of direct radiation at the collector level at midday. This makes pump control easier, as the load demand is normally low at midday and higher in the morning and afternoon. Another advantage of parabolic trough collectors is the reduction of stagnation events which also results from tracking. However, it is also important to consider the row spacing of the parabolic trough collectors. When designing the system, care must be taken to ensure that the shading and area utilization are low and that the area efficiency is as high as possible.

While concentrated collectors are suitable for applications requiring higher temperatures when using solar energy, flat plate collectors remain a promising option, especially in applications where lower flow temperatures are sufficient. However, in addition to technological considerations, the economic feasibility of these technologies must also be thoroughly assessed, taking into account potential cost variations and uncertainties associated with real applications.

The studies and comparison that were carried out show that concentrated collectors such as parabolic troughs are interesting for heating networks in Germany and most probably in Central Europe and are useful in sunny locations. The use of these technologies needs to be investigated further.

5. Outlook

Further investigations will be carried out as part of the project Pro-Sol-Netz (May 2024 to April 2027) and IEA SHC Task 68 (April 2022 to March 2025). The TRNSYS simulation model and the assumptions made should be further optimized. In addition, different concentrated collector technologies can be compared with each other and further case studies can be carried out. In this described case study, mainly the parabolic trough collector PTC 1800 was investigated. The investigation of other parabolic trough collectors is also interesting. In addition, a comparison with other standard collectors, such as vacuum tube collectors, proves to be relevant.

Pro-Sol-Netz aims to provide developments and evaluations in order to successfully establish and use concentrated collectors in the markets for district heating systems and process heat in central Europe, both technically and economically. The availability of knowledge and calculation tools for municipal utilities and planning offices plays a central role in enabling them to plan and implement concentrated solar thermal systems.

The work in Pro-Sol-Netz focuses on carrying out the developments and evaluations, including the first pilot plants in Germany, in order to be able to use and establish concentrated collectors for heating networks and process heat successfully in the German markets, both technically and economically, once the project has been successfully completed. These solar collectors should not be seen as competition to other renewable energy technologies such as heat pumps, but as a necessary technology for process heat and heating networks. All scenarios for the future energy mix of a decarbonized Germany show a strong increase in heat pumps, geothermal energy and solar thermal energy. The project-specific conditions lead to the most economical selection of the technologies mentioned, with alternatives to heat pumps being required for supply temperatures above 95 °C in particular.

In Pro-Sol-Netz, the thermal yield of commercial parabolic trough systems is scientifically measured and monitored. The measurement data is used for validation and as practical proof of the performance of concentrated collectors in the future-oriented sectors of heating networks and process heat. Existing simulation tools for calculating and predicting system yields, such as SCFW and Greenius, are being further developed for use with concentrated collectors. The ROKA³ heating network calculation software is also being improved for the integration of solar thermal heat production, thereby supporting the validation and dissemination of research results (SCFW, 2024) (Greenius, 2024) (ROKA³, 2024).

In Pro-Sol-Netz Solites leads two work packages and supports other work packages by contributing expertise, carrying out modeling and simulations and developing simulation tools, among others. Solites is also active in the international exchange of knowledge in the parallel ongoing IEA SHC Task 68.

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Pro Sol Netz

SHC SOLAR HEATING & COOLING PROGRAMME INTERNATIONAL ENERGY AGENCY

Supported by:

Federal Ministry for Economic Affairs and Climate Action

on the basis of a decision by the German Bundestag

The project „Pro-Sol-Netz“ has received funding from the German Ministry for Economic Affairs and Climate Action on the basis of a decision by the German Bundestag.

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