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Stagnation in Large-Scale Solar Thermal Systems? Experiences From Recent Installations as Motivation for Heat Pipe Collectors in a Novel System Design

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Abstract. Large-scale solar thermal systems supplying heating networks can make a significant contribution to the decarbonization of the heating sector and are becoming increasingly relevant in practice. The first part of the paper analyses 30 realized systems in Germany focusing on collector area, heat storage capacity and stagnation events. More than 60 % of these systems have heat storage capacities smaller than 100 l/m² collector area. Nevertheless, a third of the systems reaches an annual solar fraction of over 20 %. Our investigations for such dimensioned systems report a number of 20 to 43 stagnation days per year, depending on the storage capacity. The relevance of stagnation load motivates our research activities to avoid its negative consequences in large-scale systems. The second part of the paper describes the development of evacuated tube collectors with inherent overheating prevention as well as the outdoor tests we carried out with various prototypes at our sun tracker. The collector concepts are based on heat pipes with temperature limitation to 125-135 °C in the solar circuit and are therefore able to avoid evaporation of the heat transfer medium. Due to lower stagnation loads, we investigate the possibility of using polymeric pipes instead of steel pipes for the solar circuit and discuss an integrated system concept. The innovative collector and system design are implemented in a demonstration plant that we will monitor during the construction phase and in operation.

Keywords: Large-Scale Solar Thermal Systems, Stagnation Load, Heat Pipe, Overheating Prevention, Cost Efficiency

1. Introduction

The share of district heating in the German heat supply is currently around 15 % and should be increased rapidly in the next years. The recommendations and targets range from 25 % to 30 % in the context of 2030 and 2045 scenarios [1] [2]. This need to be achieved with an increasing application of renewable energy sources, which offers an enormous potential for the large-scale use of solar heat. Especially high-efficiency collectors, such as evacuated tube collectors (ETC), are well suited to supply the still high temperature demands in typical district heating networks (DHNs). In addition to reducing climate-damaging emissions, the use of solar thermal energy can help to diversify the heat supply and thus increase the resilience of the energy sector. For several years, large-scale solar thermal systems have increasingly been used to feed heating networks in Germany and a trend towards ever-larger systems is recognizable [3]. A total number of 61 systems are already in operation and 16 systems are currently in the implementation phase, which represents a cumulative collector area of approx. 366,000 m². Other 67 systems with approx. 221,000 m² are currently in preparation. The installed capacity is expected to double by 2026 compared to 2024. [4]

With increasing system size and solar fraction (SF), the stagnation problem also becomes more relevant, as the analysis of realized systems in this article shows. One possible approach to avoid this issue is the use of specially designed heat pipe collectors with temperature limitation. In addition to reducing possible risks caused by stagnation, this kind of intrinsically safe overheating prevention also offers optimization potential in the planning and implementation process of solar circuits. For example, the pressure maintenance can be simplified and polymeric pipes can be used instead of steel pipes. In the district heating sector, the saving potential of polymeric piping systems is estimated to be around 30 % of the total piping costs, depending on individual conditions (e.g. ground properties and pipe diameter) [5]. In the R&D project *HP-BIG* funded by the Federal Ministry for Economic Affairs and Energy (03EN6011A-C), we are developing such collectors as large-area modules as well as an innovative system concept. In the context of a demonstration plant (LIVE-Lab), we are realizing this approach into practice and evaluating system operation.

2. Recent installations

2.1 Scope of analysis

Based on the periodic statistic of installed systems and locations by Solites [4], we examined 30 projects with ETC and an area > 1,000 m² that have been already realized or are currently being implemented in Germany (see Fig. 1). In addition, we conducted several interviews with plant operators to get further technical information such as temperatures, storage tank sizes and number of stagnation days. The results represent the current status of large-scale solar thermal energy in Germany and supplement our previous article from 2023 [6].

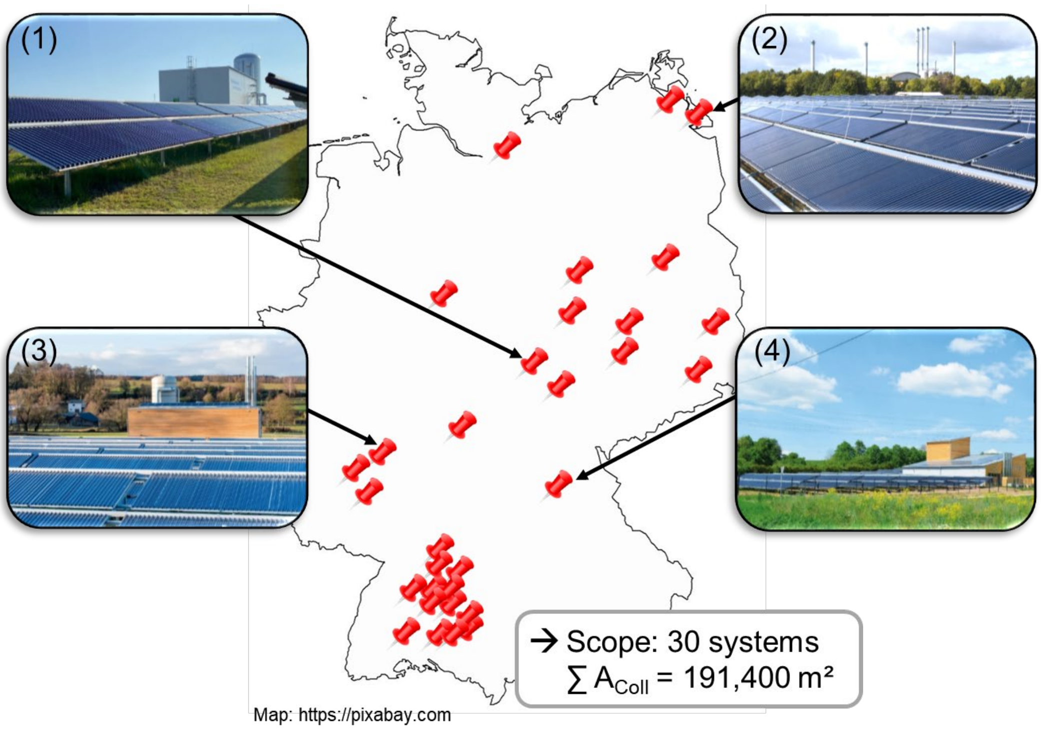


Figure 1. *Map with the 30 locations of the analyzed ETC plants > 1,000 m² and the examples (1) Mühlhausen [7], (2) Greifswald [8], (3) Ellern [9] and (4) Hallerndorf [10]*

The majority of the considered systems (53 %) feed into a smaller DHN or bioenergy village. The remaining 47 % of the systems feed into classic DHNs of a city, which usually requires higher feed-in temperatures. In Fig. 2, the supply and return temperatures of all heating networks are plotted in dependency on the seasonality (summer vs. winter). The supply temperatures are usually regulated depending on the ambient temperature, so that higher values are set in winter. In contrast, the return temperature is typically lower in winter due to the higher space-heating load. The median value of return is 55 °C in winter and 60 °C in summer. Three of the data sets show temperatures below 45 °C regardless of seasonality, which favors efficient collector operation. The data of the supply temperature is more scattered. Especially the values of major city networks stand out from the average due to the typically higher heat load profiles. The median value of the supply temperature varies between 90 °C (winter) and 80 °C (summer). In summer, which is the more relevant period to gain solar yield, the supply temperatures are below 80 °C for more than 50 % of the networks considered and therefore well suited for the use of ETC.

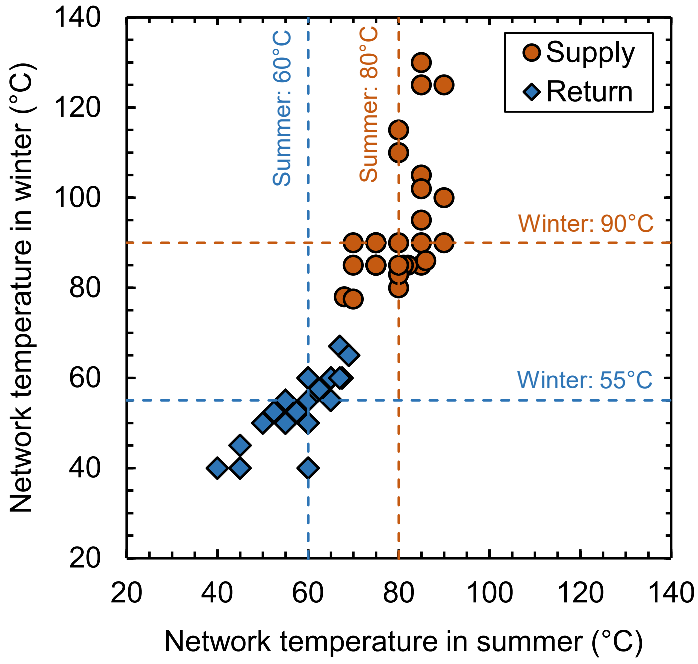


Figure 2. *Network temperatures in winter over network temperature in summer for the 30 considered locations*

2.2 System dimensioning

In addition to the most common design parameters, we studied the capacities of thermal energy storages (TES) in relation to the collector area. In general, the TES capacities of the considered systems vary widely. The analysis shows that, apart from very few exceptions, large TES (e.g. seasonal heat storages) are extremely seldom - usually for space and cost reasons. The median value is 89 l/m², whereby these capacities are often also used as multifunctional TES by other heat generators. The monitoring results of 48 systems in the Austrian study report an almost similar storage dimensioning of 82 l/m² [11].

Fig. 3 illustrates the distribution of SF and TES volume of the 30 systems considered, specifying the type of DHN (urban network and small bioenergy village). In general, the highest SF are achieved in bioenergy villages, although these do not necessarily have the largest specific TES capacities. The urban-based DHNs exhibit significantly lower SF and usually lower TES capacities. Nevertheless, some large specific TES capacities are located in urban DHNs with low SF, which is due to the high number of different heat generators supplying the multifunctional TES. A number of 12 systems (40 %) reach SF higher than 20 %, whereby a half of these systems have only TES capacities smaller than 100 l/m². In those cases, the collector field is designed to completely replace other heat generators (e.g. biomass boiler) during the summer periods. Thus, several plant operators reported that unpleasant start-stop behavior of the biomass boilers can be completely avoided and fuel as well as emissions can be saved. However, this dimensioning often leads to overcapacities, resulting in corresponding stagnation events. In order to prevent stagnation, a TES size of approximately 350 l/m² is necessary, as we determined by system simulation for SF = 20% (collector area 3,000 m²) and an average summer load. Compared to the median value in our study, the required TES must have four times the capacity.

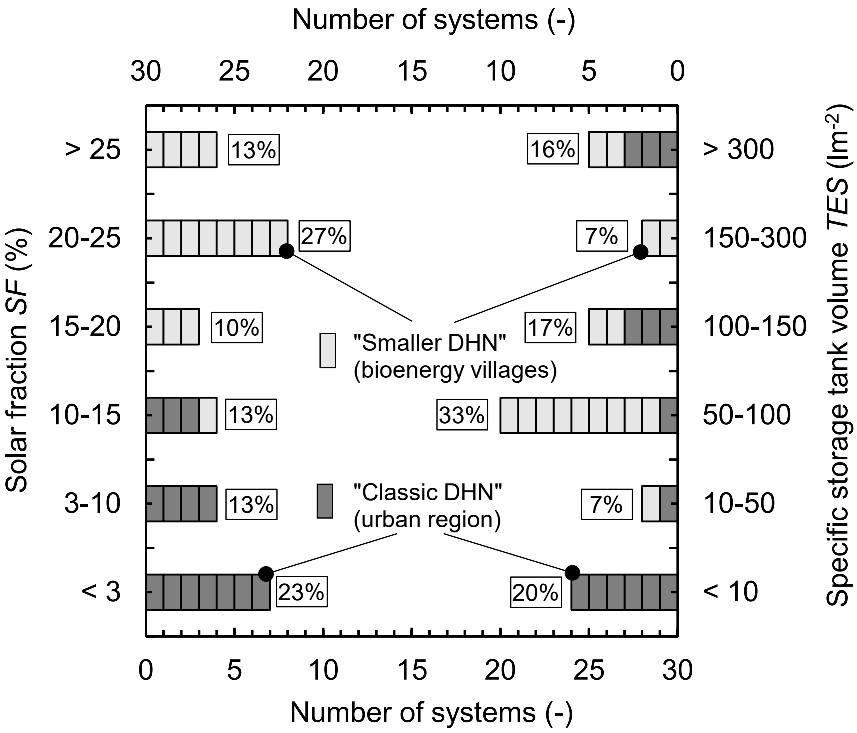


Figure 3. *Distribution of solar fraction (SF) and specific storage tank volume (TES) of the 30 systems considered. Each box represents a system, whereby the type of DHNs is specified (classic urban network and small bioenergy village)*

2.3 Stagnation events

We investigated the amount of stagnation events using measurement data, experience reports or plant simulations of 24 systems. The data is suitable to determine a dependency between stagnation days and SF. Oversized collector fields lead to more overcapacities in summer times and thus to a higher relevance of stagnation events. The correlation is affected by technical parameters (e.g. TES capacity) or by data source (measurement/ simulation) and results in a corresponding scattering. Regarding TES capacity, we identified a storage volume of 70 l/m² as a relevant value for clustering the results. The value of 70 l/m² also represents the minimum dimensioning recommendation for small and decentralized solar thermal systems with ETC [12]. In Fig. 4, the stagnation days are plotted against the SF for the TES criteria less and greater than 70 l/m². Only a single data set with ≤ 70 l/m² deviates significantly from the regression curve due to the additional supply of an industrial process with high resulting summer loads. For a typical system configuration with an annual SF of 20 %, a stagnation number of 20 to 43 days per year is expected. This system state must be given an appropriate attention in designing large-scale solar thermal systems. In practice, the handling of stagnation should be intrinsically safe, for example by draining the collector field [13] or using suitable avoidance strategies [14].

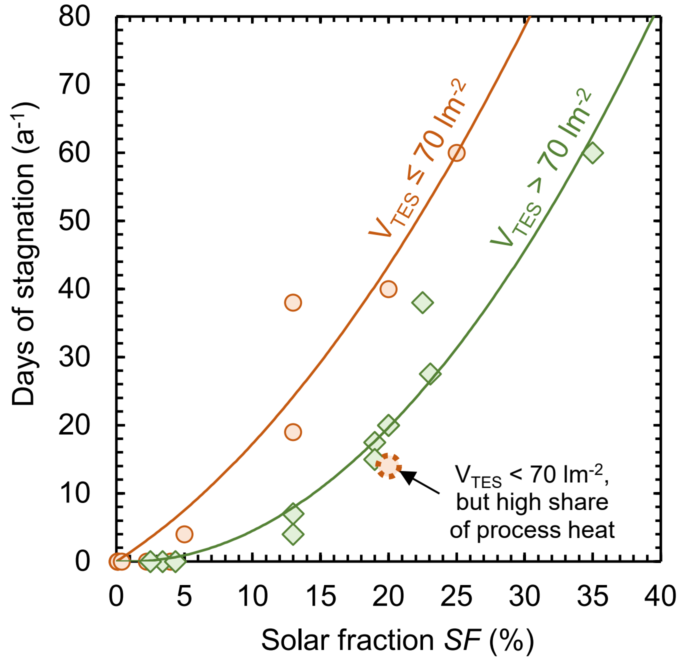


Figure 4. *Annual stagnation days over solar fraction for TES ≤ 70 l/m² and > 70 l/m² based on 24 data sets*

3. Large-scale collectors with heat pipes

3.1 Collector variants

Stagnating collectors lead to overheating and production of steam, which spreads in the piping system at high temperatures. The components used must be able to withstand these thermomechanical loads and large cooling or compensation systems must be installed. Heat pipes with temperature limitation can prevent overheating in collectors and reduce risks and costs, as already successfully demonstrated in small and decentralized solar thermal systems [15].

In the scope of this paper, we focus on transferring this approach to large-area collectors for supplying DHNs. Thereby we address different optimizations regarding shut-off, collector performance and material usage. Our current developments of heat pipe collectors are based on a large-area ETC solution (No. 0), which is already available on the market. The 13 m² module has full vacuum tubes, a simple rear-side reflector, whereby the used copper absorber fins are selectively coated on both sides. In variant No. 1, we used cost-effective DEWAR tubes in combination with a compound parabolic concentrator (CPC) instead of the full vacuum tubes. In variant No. 2, we used the CPC reflector in combination with the originally used full vacuum tubes. Variant No. 3 is essentially based on No. 2, whereby we replaced the copper absorber fins by a stainless-steel version. The absorber fins of No. 3 are also coated on both sides, but the coatings have a higher emissivity. A special aspect of No. 1 is that absorption occurs on the inner glass tube, so the heat transfer to the heat pipe is much more relevant for the overall collector efficiency. Therefore, we have also investigated an optimized variant No. 1*, which exhibits a higher internal heat transfer coefficient. No. 1* was only realized in form of a small collector prototype so far. All the considered collector variants were designed in cooperation with the companies AKOTEC and NARVA. Tab. 1 gives an overview of the main specifications. Fig. 5 shows one of the collector prototypes during the performance measurement.

Table 1. *Specifications of the considered heat pipe collectors*

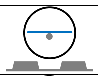
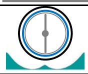
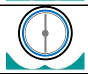
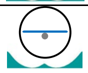
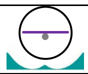
Variant	Tube / Reflector	Description
No. 0		Full vacuum tubes with absorber fins and simple reflector, corresponds to the state of development
No. 1		Evacuated tubes with glass absorber (DEWAR concept) and CPC-reflector
No. 1*		No. 1 with optimized internal heat transfer coefficient (only indoor measurement with small collector prototype)
No. 2		Full vacuum tubes with absorber fins (as No. 0) and CPC-reflector
No. 3		Full vacuum tubes with stainless steel absorber fins and CPC-reflector

Figure 5. *Outdoor performance measurement of a large-area collector prototype according to ISO EN 9806 [16]*

3.2 Collector performance

We carried out outdoor performance measurements on our sun tracker (see Fig. 5) with the collector prototypes described in Tab. 1. The test procedure was based on the ISO EN 9806 [16] but was extended to high temperature levels, to determine the shut-off behavior of the heat pipes. Due to the different tube and absorber types as well as different reflector shapes, we determined the bidirectional IAM factors (incidence angle modifier) for each variant. The optimized DEWAR variant No. 1* (small module) was only tested at normal incidence on the sun simulator (indoor). We assumed that the optical properties and thus the IAM factors are identical to No. 1.

Fig. 6 shows the collector efficiency of all configurations over the average fluid temperatures at a hemispherical irradiance between 900 and 1,050 W/m². All variants show a significant kink in the efficiency curve as a result of the heat pipe-based temperature limitation. The kink points occur in the range between 76 °C and 86 °C, depending on collector variant and transferred heat flux. The extrapolation of the measuring points after the kink point leads to maximum temperatures between 125 °C and 135 °C, which represents a significant reduction compared to the stagnation temperature of approx. 300 °C of the ETC without temperature limitation (e.g. No. 0, benchmark). The considered collector designs differ in both the zero-loss coefficient and the heat loss coefficient in the operating range (decrease in the curves before reaching the kink point), which is especially due to the different optical and thermal properties. The collector performance coefficients as well as the IAM factors are given in Tab. 2-4 (see appendix).

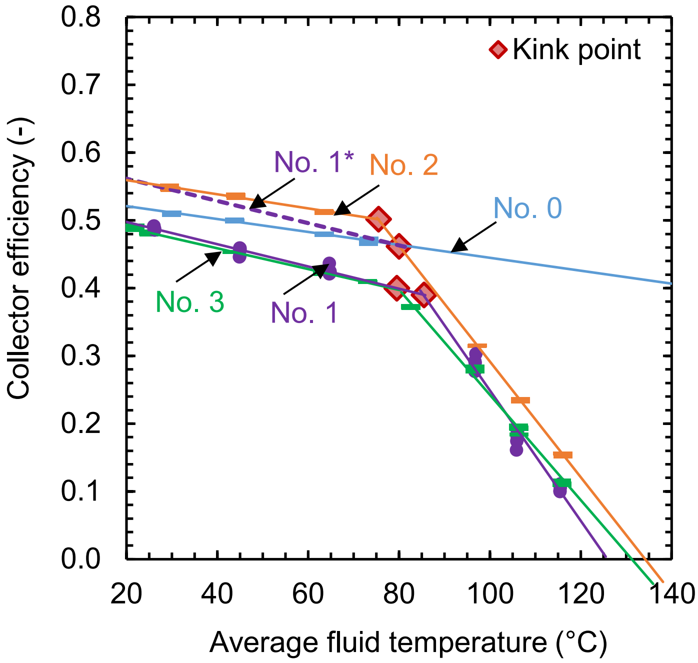


Figure 6. *Collector efficiency as beam value of all configurations over the average fluid temperature at normal incidence and hemispherical irradiance between 900 and 1,050 W/m²*

The focus on this paper is more on evaluating the influences of the different designs on the performance parameters. For this reason, we have assessed the solar yield using simple gross heat yield simulations with the ScenoCalc-Tool, whereby the heat pipe shut-off behavior was neglected. Fig. 7 shows the results of variants No. 1-3 in comparison to the benchmark at the German location Würzburg and an average collector temperature of 75 °C.

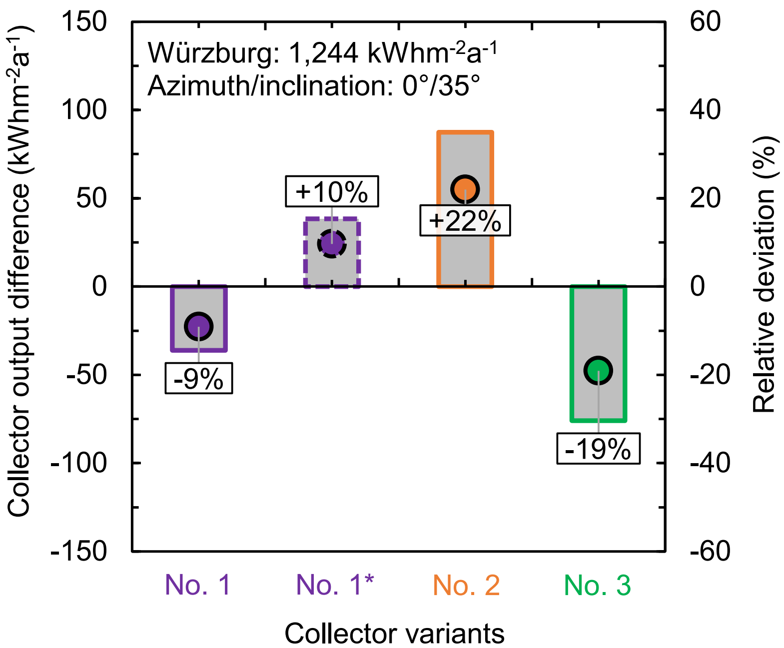


Figure 7. *Collector output difference of the v No. 1-3 in comparison to the benchmark based on gross heat yield simulations at the German location Würzburg and an average temperature of 75 °C*

The variant No. 2 with copper absorber fins and CPC reflector reach an improvement of 87 $kWhm^{-2}a^{-1}$, which represents an increase by 22 % in comparison to the benchmark (No. 0). In case of the original DEWAR concept (No. 1) the output decreases by 9 %, whereby the optimized variant (No. 1*) let increase the output by 10 %, showing the importance of a high internal heat transfer coefficient. The absorber fins made by stainless steel (No. 3) lead to a significant decrease of 19 %, which represents the worst result in the test series.

3.3 Stagnation behaviour

Beside the performance evaluation, we have experimentally tested also the stagnation behaviour at our sun tracker (s. Fig. 4). We first heated the solar circuit to a temperature of approx. 100 °C and then deactivated the pump at high irradiation, which represents the begin of the stagnation event. Fig. 8 shows collector temperatures as well as the hemispherical irradiance at the collector area for an exemplary stagnation test of variant No 1. The temperatures at the two measuring points (contact sensors at inlet and outlet) rise significantly shortly after the start of stagnation and achieve a maximum temperature of 127 °C. The collector was tracked during stagnation to ensure the maximum irradiance.

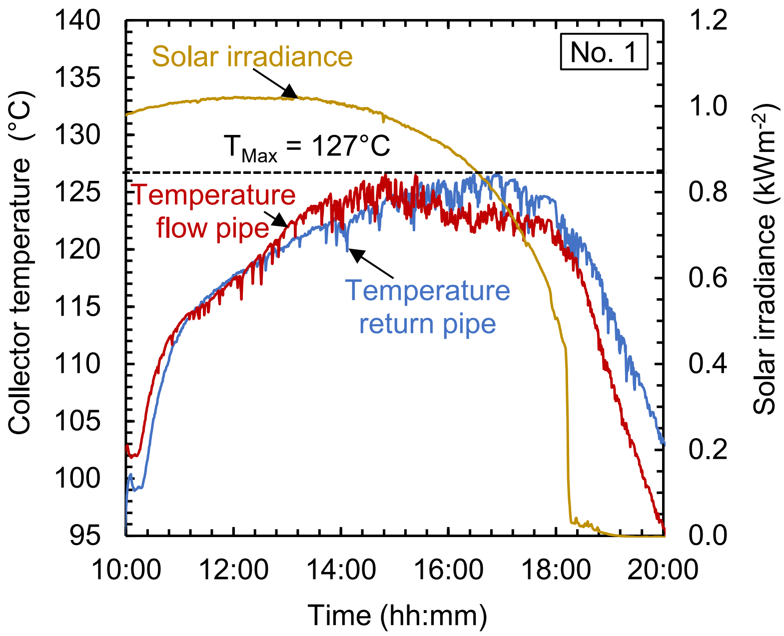


Figure 8. *Collector temperatures and hemispherical solar irradiance over the time of a stagnation day with variant No. 1 at our sun tracker*

4. Innovative system concept

4.1 Field hydraulic and piping material

The heat pipe collectors in consideration allow a significant simplification of the solar circuit hydraulic, especially in case of large-scale collector fields. The large-dimensioned manifold pipe inside the collector represents a kind of integrated route line. This allows up to 250 m² of such collector modules to be connected in a hydraulic row. In ground-mounted installations, the collector row often corresponds to the hydraulic line. Parallel circuits within a collector row are therefore not necessary. Compared to systems with direct-flow collectors we determined a reduction of total piping length by around 80 % for an exemplary system with 14 rows and 3,000 m² collector area, which reduces material and installation costs. The intrinsically safe avoidance of stagnation loads allows the use of cheaper components and offer the possibility of further cost-savings.

In cooperation with pipe manufacturers, we designed a hydraulic concept for the solar circuit based on polymeric pipes (see Fig. 9). We investigated two pre-insulated flexible polymer pipe systems with an inner pipe made of polyethylene multilayer structure (PE-Xa), one with a standard pipe and the other with a fibre-reinforced composition with higher temperature resistance. For lifetime prediction, we considered the linear damage accumulation by using the Miner's Rule [17] [18] as well as thermal stress due to rapid temperature changes by thermal cycling tests according to ISO 19893:2018 [19]. The evaluation is based on typical operating conditions (e.g. supply and return temperatures) by using heat pipe collectors such as No. 2 of Tab. 1. Both methods confirm that the considered pipe material can achieve a lifetime of more than 25 years.

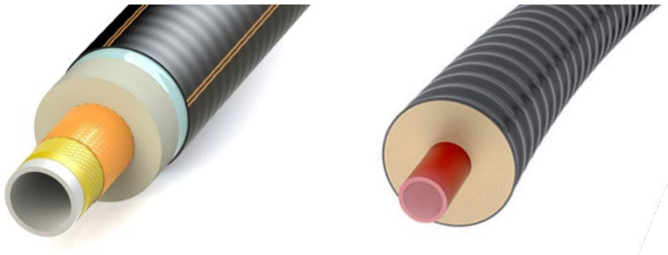


Figure 9. *Illustration of two possible piping systems based on polymeric material [17] [18]*

4.2 Monitoring setup

We realized a demonstration collector row (LIVE-Lab) with an area of 156 m² based on this innovative system concept in the context of the current R&D project *HP-BIG*. The LIVE-Lab row features the innovative variants No. 1 and No 3 and is part of a solar heating network with a total collector area of approx. 2,900 m², which consists of collectors of variant No. 0. The heating network demand is specified by supply temperatures between 75 - 90 °C and return temperatures around 45 °C. Fig. 10 illustrates the general setup of the LIVE Lab as an addition to a large collector field with separate hydraulics. To evaluate performance, yield and occurring maximum temperatures, a scientific monitoring system was installed. The plant is just going into operation and we expect reliable results in mid-2026.

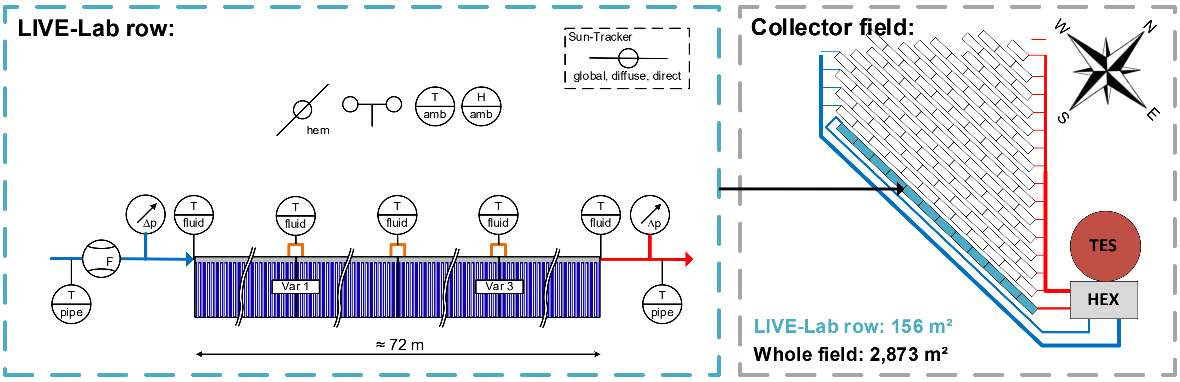


Figure 10. *Monitoring setup of the LIVE Lab (left) as an addition to a large collector field with separate hydraulics (right)*

4.3 Experiences from implementation

Already during the installation of the polymeric piping system, our partners gained useful practical experience with the material itself and its processing. The main difference to usual steel pipe installations is that the polymeric pipes are joined by pressing prefabricated fittings together instead of being welded. Fig. 11 shows some impressions from laying and connecting the pipes of the collector field. The parallel processing of the steel pipe system, which is used in the rest of the field, impressively illustrated the differences in complexity of the assembly process as well as the overall installation effort for all participants. In addition to other aspects, the independence of specially qualified experts (welding specialists) saves costs and significantly increases flexibility in terms of scheduling, which is a relevant factor for the involved industry partners. Another crucial aspect is the significantly lower dependency on weather conditions at the construction site, due to the fact that welding work can be avoided. Our implementation partners also report that the risk of leaks is lower and the time-consuming testing of welded joints can be saved. Clear and generalizable statements regarding the saving potential of this simpler assembling of polymeric pipes are hard to find in literature. We assume this is due to the fact that the benefits depend on individual factors at the specific location, executing companies or the conditions at the construction site. In the building sector, the benefit of pressing instead of welding for joining supply lines is reported to reduce working time by up to 80% [20]. These figures are surely not applicable to SDH systems in open areas, but show the general potential of simpler installation procedures.

Figure 11. *Impressions from laying supply/ return pipes of the LIVE-Lab (left) and connecting pipes to the collector (right)*

5. Conclusion

Based on the analysed projects in Germany, we have found out that the amount of stagnation events is also relevant in large-scale solar thermal systems. Configurations with an annual SF of around 20 % achieve between 20 and 43 stagnation days per year. As we have demonstrated by means of a test campaign of four large-area collectors, heat pipes with inherent possibility of temperature limitation can significantly reduce the thermal loads. The measured maximum temperatures range between 125 °C and 135 °C and are thus significantly lower than in typical ETCs. In typical pressurized solar circuits, evaporation of the heat transfer medium during stagnation events can be intrinsically avoided without the need of external energy or additional devices. The different collector variants must be compared with the advantages and disadvantages in terms of performance and solar yields as part of a cost-benefit analysis. Two of the developed large-area collectors are already being used in a demonstration system so that we can evaluate their operation behaviour in a real plant situation and in combination with the novel system concept. If system size and SF rise further in upcoming systems, the relevance of stagnation events will increase. The essential question for the current development is how much effort can be saved in the planning, dimensioning, implementation and operation of an intrinsically safe system by using heat pipe collectors. The comparison of the resulting costs for components and installation as well as the evaluation of total investment costs and the expected heat prices are the focus of the current work.

Data availability statement

The analyses and results of this article are based on third-party data, which is restricted.

Author contributions

Bert Schiebler: Project administration, Investigation, Data curation, Visualization, Validation, Writing – original draft; **Maik Kirchner:** Investigation, Data curation; **Julian Jensen:** Conceptualization, Writing – review & editing; **Federico Giovannetti:** Funding acquisition, Supervision, Writing – review & editing

Competing interests

The authors declare that they have no competing interests.

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References

[1] R. Ehrig et al: „Wie gelingt die Dekarbonisierung der Fernwärme: Vier zentrale Herausforderungen auf dem Weg zur Klimaneutralität bis 2045." Hrsg.: Deutsche Energie-Agentur GmbH (dena). https://www.dena.de/fileadmin/dena/Publikationen/PDFs/2023/IMPULSPAPIER_Wie_gelingt_die_Dekarbonisierung_der_Fernwaerme.pdf (accessed at Mai 05, 2025)

[2] S. Hay: "Existing District Heating Networks in Context of German Climate Goals: Potentials for UrbanTurn." ISEC Conference Graz, 07th April 2022. https://www.aee-intec.at/0uploads/dateien1661.pdf (accessed at Mai 05, 2025)

[3] G. Bröer: „Größte Solarthermieanlage Deutschlands in Greifswald eingeweiht." Solarthemen Media GmbH, https://www.solarserver.de/2023/03/22/solare-waermenetze-in-deutschland-starker-zuwachs-in-2022/?utm_source=newsletter&utm_campaign=newsletter. (accessed at Mai 05, 2025)

[4] Solites: „Solarthermie in der Fernwärme: 2024 kaum Zuwachs." Solarthemen Media GmbH, https://www.solarserver.de/2025/04/03/solarthermie-in-der-fernwaerme-2024-kaum-zuwachs/?utm_source=dlvr.it&utm_medium=linkedin (accessed at Mai 05, 2025)

[5] Rehau: „Effizienz-Technologie Nahwärme." Die Zukunft von Raumheizung und Warmwasser, https://www.rehau.com/downloads/404296/kommunale-waermeinfrastruktur-referenzen.pdf. (accessed at Mai 09, 2025)

[6] B. Schiebler et al: „Solarthermische Großanlagen in Wärmenetzen: Eine Analyse von Machbarkeitsstudien und Messdaten aus realisierten Projekten.“ 33. Symposium Solarthermie und innovative Wärmesysteme, Bad Staffelstein, Mai 2023.
[7] Ritter-XL: „Offizielle Inbetriebnahme Solarpark Mühlhausen“, https://www.ritter-xl-solar.de/offizielle-inbetriebnahme-solarpark-muehlhausen. (accessed at Mai 05, 2025)
[8] Bröer, G: „Größte Solarthermieanlage Deutschlands in Greifswald eingeweiht“, Solarthemen Media GmbH, https://www.solarserver.de/2022/09/17/groesste-solarthermieanlage-deutschlands-in-greifswald-eingeweiht. (accessed at Mai 05, 2025)
[9] Solites: Bildnachweis zur Solarhermieanlage und Heizzentrale in Ellern, https://www.solare-waermenetze.de/mediathek/fotos-und-videos/?mgi_100=1529/solarthermieanlage-und-heizzentrale-in-ellern. (accessed at Mai 05, 2025)
[10] Ritter-XL: „Solarunterstützte Wärmenetze für Dörfer Hallerndorf in Oberfranken.“, https://www.ritter-xl-solar.de/anwendungen/waermenetze/hallerndorf/?nowprocket=1. (accessed at Mai 05, 2025)
[11] Ch. Fink et al: Wissenschaftliche Begleitforschung zum Förderprogramm „Solarthermie – Solare Großanlagen“ 2010-2015, https://solarthermalworld.org/wp-content/uploads/2017/03/solare_grossanlagen_2010-2015_aggregierter_bericht.pdf. (accessed at Mai 20, 2025)
[12] Viessmann: „Planungshandbuch Solarthermie“, Allendorf 2008.
[13] R. Meißner: „Technische Herausforderungen mit Großflächen-Solarthermie für die Fernwärme.“ 32. Symposium Solarthermie und innovative Wärmesysteme, Bad Staffelstein, Mai 2022.
[14] E. Frank et al: “Overheating prevention and stagnation handling in solar process heat applications”, IEA SHC Task 49, Technical Report A.1.2, https://task49.iea-shc.org/Data/Sites/7/frank_iea_shc_task49_overheatingstagnationreport_approved_v-2-3.pdf. (accessed at Mai 30, 2025)
[15] B. Schiebler et al: “Heat pipe collectors with overheating prevention in a cost-optimized system concept: Monitoring of system performance and stagnation loads under real conditions.” Solar Energy Advances, vol. 3, 100040, https://doi.org/10.1016/j.seja.2023.100040, 2023.
[16] ISO 9806: “Solar energy – Solar thermal collectors – Test methods.” Beuth Verlag, Berlin, 2018.
[17] ENEPIPE: “Rohrsysteme – Technische Information“, https://www.enerpipe.de/fileadmin/daten/02_produkte/06_Rohre-und-Verbindungstechnik/Rohrsysteme_TI_821000100_04-2021_web.pdf. (accessed at Mai 08, 2025)
[18] Brugg: „CALPEX-Fernwärmeleitung – Technisches Datenblatt“, https://www.bruggpipes.com/fileadmin/user_upload/downloads/produkte/01-nah-und-fernwaerme/calpex/calpex-anschlussverbindungen/brugg-rohrsysteme-calpex-katalog_de.pdf. (accessed at Mai 08, 2025)
[19] ISO 19893: “Plastics piping systems – Thermoplastics pipes and fittings for hot and cold water – Test method for the resistance of mounted assemblies to temperature cycling.” Beuth Verlag, Berlin, 2018.
[20] Viega: „Innovative Rohrverbindungstechnik von Viega“, https://www.produktion.de/innovative_rohrverbindungstechnik_von_viega/pressen-statt-schweissen-bei-extremen-industrieanwendungen-122.html. (accessed at Mai 09, 2025)

Appendix

Table 2. *Performance coefficients of all collector variants; heat losses are only considered with linear temperature dependency (a_2 = 0).*

Variant	Zero-loss coefficient $\eta_{0,b}$	Linear heat loss coefficient a_1	Correction of diffuse irradiance K_d
No. 0	0.520	1.152 W/(m²K)	0.940
No. 1	0.492	1.613 W/(m²K)	1.032
No. 1*	0.556	1.613 W/(m²K)	1.032
No. 2	0.552	0.976 W/(m²K)	0.955
No. 3	0.485	1.662 W/(m²K)	0.990

Table 3. *Transversal IAM factors of all collector variants.*

Var.	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°
No. 0	1.00	1.02	1.01	1.01	1.01	1.01	0.96	0.64	0.32	0.00
No. 1	1.00	1.05	1.12	1.16	1.21	1.27	0.96	0.64	0.32	0.00
No. 1*	1.00	1.05	1.12	1.16	1.21	1.27	0.96	0.64	0.32	0.00
No. 2	1.00	1.08	1.06	1.07	1.03	1.02	0.97	0.65	0.33	0.00
No. 3	1.00	1.06	1.06	1.06	1.02	1.01	0.93	0.62	0.31	0.00

Table 4. *Longitudinal IAM factors of all collector variants.*

Var.	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°
No. 0	1.00	1.00	1.00	0.99	0.98	0.96	0.93	0.87	0.67	0.00
No. 1	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.98	0.94	0.00
No. 1*	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.98	0.94	0.00
No. 2	1.00	1.00	1.00	0.99	0.98	0.96	0.93	0.86	0.66	0.00
No. 3	1.00	1.00	1.00	0.99	0.98	0.96	0.93	0.86	0.66	0.00