Solar Energy Advances 2 (2022) 100029

Contents lists available at ScienceDirect

Solar Energy Advances

journal homepage: www.elsevier.com/locate/seja

About common but avoidable faults during planning, installation, and operation of solar heating plants in industrial applications

Y. Louvet*, F. Pag, D. Ritter, C. Schmelzer, K. Vajen

University of Kassel, Institute of Thermal Engineering, Kurt-Wolters Straße 3, 34109 Kassel, Germany

ARTICLE INFO

Keywords:
SHIP
Faults

ABSTRACT

In the BEsoPro research project, multi-year measured solar yields of 13 solar heat for industrial processes (SHIP) plants in Germany are compared with planned values. The data come from plants installed between 2012 and 2019, with three collector technologies supplying heat to different industrial processes in the low-temperature range, below 100°C for all but one plant. The average collector area of the plants studied is 327 $m^2{}_{gr}$. With a high certainty, seven of the SHIP systems achieve a lower energetic performance than predicted and four systems reach the expectations. For the last two systems no conclusive quantitative assessment is made due to insufficient measurement data. A list of ten common faults and problems in SHIP plants is then defined based on the analysis of additional detailed measurement data available for eight of the 13 plants, combined with the authors' long experience with SHIP plants. Particularly common faults are the undersizing of the solar heat exchanger and the undersizing of the pump(s) in the solar collector loop. No critical problems or major component or system defects are found. Overall, most faults could be avoided relatively easily with better system planning and installation. These findings should be urgently addressed by the branch to avoid long-term damaging effects on the image of SHIP systems.

1. Introduction

By the end of 2021, at least 975 solar heat for industrial processes (SHIP) plants totalling 1.23 million m^2 had been installed worldwide according to the Solar Heat Worldwide report [1]. Even though SHIP systems still represent a minor share of the total solar thermal capacity in operation worldwide, interest for such systems is reportedly growing [1]. In Germany, a specific subsidy scheme for SHIP plants has been in place since the end of 2012. By the end of March 2021, almost 39,000 m^2 of collectors had been installed in Germany [2]. This number is low considering the substantial effort put into subsidizing SHIP plants and the technical potential available in Germany, estimated at 50 million m^2 for industrial processes and another 100 million m^2 if the trade, commerce and service sectors are considered [3]. Furthermore, no clear trend of market growth has been observed over the past years [4].

In this context it is important that installed SHIP plants reach the planned yields and operate smoothly to promote SHIP as a reliable and market-ready solution. SHIP plants must be planned, installed, commissioned, and operated properly to avoid potential errors, hampering their proper functioning and leading to lower than expected energetic performances. While the reliability of solar thermal systems (STSs) was investigated in several studies in the past, especially for small systems, there are only few detailed studies available in the literature on the long-term performance of SHIP plants. One of the objectives of the BEsoPro research project was to fill this gap by analysing multi-year measurement data from 13 existing SHIP plants in Germany to compare the achieved energetic performances with the planned ones. Besides energetic performances, detailed monitoring data from eight of the 13 plants were used to identify sources of inefficiency. After a literature review of existing studies related to faults in SHIP systems and STSs at large, the main results of the yield and detailed analysis are summarised in this paper. Based on the project findings and the authors' long experience with SHIP plants, a list of ten common faults and problems in SHIP plants is compiled, with illustrative examples and measures to implement in order to avoid them. The aim is to raise awareness about these issues so that they can be avoided in the future.

2. Faults in SHIP systems and solar thermal systems in the literature

2.1. SHIP systems

There are only few studies in the literature dealing with the long-term reliability and performance of SHIP systems. Most of the case studies found focus on the design and simulated performance of SHIP systems and not on operational experience. In addition, some of the few detailed studies found are old, which reduces the relevance of their find-

* Corresponding author.
E-mail address: solar@uni-kassel.de (Y. Louvet).

https://doi.org/10.1016/j.seja.2022.100029
Received 29 August 2022; Received in revised form 7 November 2022; Accepted 7 November 2022
Available online 12 November 2022

List of symbols

f_s	solar fraction
H	annual global horizontal solar irradiation in kWh/a
Q_{sol}	annual solar collector yield in kWh/a
ΔT_{log}	logarithmic mean temperature difference in K
η_s	(pseudo) solar utilisation ratio
σ	standard measurement uncertainty
Subscripts	
ap	aperture (collector area)
c	outlet of the collector field (solar collector yield)
gr	gross (collector area)
meas	measured
plan	planned
s	delivered to the heat storage (solar collector yield)
u	useful solar collector yield
Abbreviations	
CPC	compound parabolic collector
DWD	German Meteorological Service (Deutscher Wetterdienst)
ETC	evacuated tubular collector
FPC	flat plate collector
HTF	heat transfer fluid
LFC	linear Fresnel collector
LMTD	logarithmic mean temperature difference
PTC	parabolic trough collector
SHIP	solar heat for industrial processes
STS	solar thermal system

ings. This is confirmed by Faure et al. [5] in their literature review related to fault detection in large STSs, who wrote that the "most complete research studies on reliability of solar thermal systems date back from several decades ago" and that recent studies mostly focus on small-scale STSs.

Nevertheless, relevant studies on SHIP systems are analysed and an overview of the STSs they describe is presented in Table 1 . Besides general information about the SHIP plants and the supplied industrial processes, the faults and problems of the plants as well as performance indicators given in the studies are listed. The listed studies were primarily identified in earlier literature reviews on large-scale STSs and SHIP systems by Lauterbach [6,7], Sharma et al. [8] and Tasmin et al. [9]. The list is complemented with a few additional works. In total, 32 SHIP systems are listed, based on 21 different studies. Most studies deal with one or two systems except for two of the oldest ones by Kutscher and Davenport [13] and Karagiorgas et al. [14] which provide relevant information about six, respectively eight SHIP systems. More recently, as a result of an Austrian research project, the analysis of several SHIP plants is available in different publications [10–14]. The level of detail found in the literature also varies greatly. While most studies only dedicate a section to performance and fault analysis, those by Kutscher and Davenport [13], Lauterbach [6], Fink et al. and Becke et al. [10–14] and Möllenkamp [15] go deeper into detail as they are specifically dedicated to operation analysis and fault detection.

The systems described cover a wide range of industrial sectors and processes. Furthermore, a large spectrum of collector technologies is considered, both non-concentrating ones, namely flat plate collectors (FPCs) and evacuated tube collectors (ETCs), as well as concentrating ones, namely compound parabolic collectors (CPCs), parabolic trough collectors (PTCs) and linear Fresnel collectors (LFCs). Most systems use a liquid heat transfer fluid (HTF), except for four using air as HTF [14,16].

The faults and problems identified by the authors are very diverse and most of the time plant specific. A few trends can however be identified. First of all, in the reports on the earliest installed systems [16,17], damage to or even failure of components (mostly collectors, but also heat storage, sensors, controller, data logger) is often reported which is not the case for the systems installed later. This could be positively interpreted as a result of technology improvement over the last decades. Besides components flaws, several other issues are reported for more than one system:

- undersizing of components, notably heat exchangers and pumps [6,10,16–18],
- flow unbalances in the collector field or in the storages [16,19,20],
- leakages in the solar collector loop [15,16,21],
- higher than expected heat losses notably from the piping and heat storages [6,12,16,17],
- high capacitive thermal losses because of the important thermal masses in the hydraulic circuits [15,16],
- unexpected load profiles leading to period when solar yields are lost due to unwanted standstill [15–17],
- auxiliary heater heating the solar heat storage more than required [17,21,22],
- dirt on the collectors, especially because of boiler exhaust [16,17],
- diverse issues with the tracking systems for concentrating systems [15,16,23],
- improper behaviour of plant operators [6,16].

Concerning the performance of the plants, the most commonly reported indicator is the solar utilisation ratio η_s. A comparison between studies is however difficult as the reference period for the calculation of η_s varies. It is sometimes a year [6,14,15,18,21,24,25], a few months [10], a month [23,26,27], a day [17,28] or even a random number of days [16]. The solar fraction f_s is reported as further indicator in a few studies [11,12,17,18,21]. Some authors also give a comparison between planned and achieved performance, based on different indicators [6,10–12,14,16,18,21,28]. Overall, of the 13 systems for which a comparison is presented, the expected performance is not reached in most cases except for three systems [10–12]. For two of these three systems shortcomings in the simulations are identified. Fink et al. [11] specify that a simplified simulation not considering all supplied processes is the main reason for the underestimation of the solar yield. Similarly, in Fink et al. [12] one of the heat sinks was not considered and the storage heat losses were underestimated in the simulation, which are the main reasons for the underestimation of the solar yield. Regarding systems that underperform, Kutscher and Davenport [16] mention that the main reasons for the discrepancies are the overestimation of collector performances and the failure to estimate piping losses. Considering that the measured useful collector yields vary from -55 to -79 % of the planned ones, the explanation must be put in its context, as advanced simulations tools were not available in the late 1970s at the time of the study.

It should also be noticed that only a few studies [6,15,29] quantified or even addressed measurement uncertainties, so that it is not possible to assess the quality of the measured data presented in the reports and essentially qualitative conclusions can be drawn from the studies found.

2.2. Other solar thermal systems

Besides SHIP systems, the reliability of STSs at large and the determination of the most common faults and problems were studied in several projects in the past. Faure [30] notably gives a comprehensive overview of relevant studies in her thesis.

From a general perspective, several authors proposed extensive lists of possible faults in STSs [30–32]. The faults are sorted by component (collector, storage, etc.), system part (solar collector loop, discharge loop, etc.), or project phase (planning, installation, and operation). More specifically, Brandstetter [33] defined three standard large STSs present on the Austrian market and listed some typical faults that may affect them with the aim of developing algorithms able to detect these faults.

Other studies focus on the evaluation of a selection of existing STSs, with the aim of identifying common mistakes and optimisation poten-

Table 1
Overview of the analysis of the faults and problems as well as the performance of SHIP systems from the literature.

Application	Installation year / country	Collector field / solar heat storage details	Process temperatures (return..flow)	Identified faults and problems	Performance analysis	Reference
Can washing	before 1979 / USA	FPCs/PTCs: 414/268 m^2 Storage: 106 l/m^2	10..91°C	- solar heat integrated at process level: STS idle for several week while process shut down for operational reasons - several absorber pipes of the PTCs broken due to thermal expansion / storm - data logger and flow sensor failures	-	[16]
Textile dyeing	before 1979 / USA	ETCs: 621 m^2 Storage: 49 l/m^2	Flow temperature: 88°C	- capacitive thermal losses at night - undersizing of primary solar collector loop pump - poor insulation of collector headers and wet insulation resulting in higher heat losses - broken glass of ETCs due to installation / thermal shock after stagnation - leakages in the solar collector loop due to overtightened fittings - decreased reflectivity of the reflectors behind the ETCs due to boiler stack emissions	Period: 3 days η_s (based on $Q_{sol,u}$): 9.7 % Achieved vs. planned $Q_{sol,u}$: -74 %	[16]
Concrete block curing	before 1979 / USA	Multiple-reflectors linear concentrators: 621 m^2 Storage: 221 l/m^2	Flow temperature: 57 to 82°C	- deterioration of the black chrome selective surface on the absorber pipes - cracks on the mirrors due to thermal expansion - thermosiphon night cooling causing freezing (secondary side) and burst of the solar heat exchanger - loss of HTF through the pressure relief valve due to overheating - data logging issues - problem with the tracking system in winter due to the increased viscosity of the oil used in the motors	Period: 262 days η_s (based on $Q_{sol,u}$): 9.8 % Achieved vs. planned $Q_{sol,u}$: -76 %	[16]
Soybean drying	before 1979 / USA	FPCs (air): 1,217 m^2 No heat storage	Flow temperature: 68 to 79°C	- dirt (soybean chaff and oil) on the collector glazing requiring regular cleaning - lower than expected air flow rate in the solar collector loop - inappropriate plant operation practice, shutting down the supplied process for maintenance during the day every two days - data logging issues - wet pipe insulation	Period: 290 days η_s (based on $Q_{sol,u}$): 25.6 % Achieved vs. planned $Q_{sol,u}$: -79 %	[16]
Lumber drying	before 1979 / USA	FPCs: 223 m^2 Storage: 84 l/m^2	Flow temperature: 43 to 71°C	- overheating of the heat storage causing failure and leakage of a connecting pipe - several issues with the collectors: insulation outgassing, broken inlet connections due to overtightening - issues with flow sensors and differential thermostat - issue with proper collector draining (drainback system)	Period: 180 days η_s (based on $Q_{sol,u}$): 33.5 % Achieved vs. planned $Q_{sol,u}$: -59 %	[16]
Fruit drying	before 1979 / USA	FPCs (air): 1,950 m^2 Storage (rocks): 27 l/m^2	Flow temperature: 60 to 66°C	- deterioration of collector glazing (yellowed, cracks) - regular vandalism at night causing damage on some components - problem of flow distribution and pressure drop inside the rock storage - higher than expected duct losses - data logging and controller issues	Period: 181 days η_s (based on $Q_{sol,u}$): 19.9 % Achieved vs. planned $Q_{sol,u}$: -55 %	[16]
Bottle washing	1993 / Greece	FPCs: 308 m^2 Storage: 19 l/m^2	Flow temperature: 60 to 75°C	- corrosion issues (not specified) - damaged FPCs (cracks in the glass, deformation of the frame, rusting of the absorber plates) - poor insulation of the heat storage	Period: 1 typical day η_s (based on $Q_{sol,u}$): 23.5 % f_s: 14.7 %	[17]
Clothes washing	1993 / Greece	FPCs: 55 m^2 Storage: 27 l/m^2	Flow temperature: 40 to 90°C	- minor corrosion issues (not specified) - damaged FPCs (cracks in the glass, deformation of the frame, rusting of the absorber plates) - open heat storage with severe corrosion issues (replaced with a closed one)	Period: 1 typical day η_s (based on $Q_{sol,u}$): 16.2 % f_s: 6.7 %	[17]
Feed water pre-heating (textile dyeing and finishing)	1993 / Greece	FPCs: 180 m^2 Storage: 56 l/m^2	-	- higher than expected cold water temperature due to natural (solar) heating of the cold-water storage - insufficient insulation of the heat storage - undersizing of the heat exchanger immerged in the solar heat storage	Period: 1 typical day η_s (based on $Q_{sol,u}$): 16.9 %	[17]
Yoghurt maturing / hot water	1993 / Greece	FPCs: 170 m^2 Storage: 12 l/m^2	Flow temperature (yoghurt maturing): 45°C	- overdimensioning of the STS - solar heat storage unnecessarily heated by the steam boiler of the factory	Period: 1 typical day f_s: 3.3 %	[17]

(*continued on next page*)

Table 1 (*continued*)

Application	Installation year / country	Collector field / solar heat storage details	Process temperatures (return..flow)	Identified faults and problems	Performance analysis	Reference
Hot water (various tannery processes)	1993 / Greece	FPCs: 308 m^2 Storage: 44 l/m^2	Flow temperature: 40 to 90°C	- corrosion issues (not specified) - damaged FPCs (cracks in the glass, deformation of the frame, rusting of the absorber plates) - soot deposition on the collector surface - malfunctioning of the floats of the open storage tanks	Period: 1 typical day η_s (based on $Q_{sol,u}$): 7.3 %	[17]
Greenhouse heating	1994 / Greece	FPCs: 80 m^2 Storage: 55 l/m^2	Flow temperature: 45°C	- no insulation of the piping of the primary solar collector loop	Period: 1 typical day η_s (based on $Q_{sol,u}$): 26.5 % f_s: 100 %	[17]
Egg powder production	before 1997 / India	FPCs: 2,560 m^2 Storage: 90 l/m^2	22..85°C	-	Period: 1 day η_s (based on $Q_{sol,u}$): 45 to 58 % depending on the month considered Achieved vs. planned: -32 % (energy and period considered unclear)	[28]
Textile fibre treatment	1999 / Greece	FPCs: 50 m^2 Storage: 40 l/m^2	Flow temperature: 90°C	- shading of the collector field from the surroundings	-	[17]
Feed water pre-heating / Cleaning in Place (dairy industry)	2000 / Greece	FPCs/CPCs: 614/111 m^2 Storage: 14 l/m^2	-	- soot deposition from the heavy oil steam boiler on the collector surface	-	[17]
Beer brewing / space heating	2009 / Germany	ETCs: 736 m^2_{ap} Storage: 150 l/m^2_{ap}	Flow temperature: > 100°C	-	Period: 2 years η_s (average, based on $Q_{sol,u}$): 20.1 % f_s (average): 11.3 %	[24]
Electroplating / hot water / space heating	before 2010 / Germany	ETCs: 400 m^2 Storage: 19 l/m^2	Flow temperature: 70°C	- flow rate through the five parallel solar heat storages unbalanced, resulting in storage mixing - presence of air in the solar collector loop - problem with the controller leading to stagnation of the collector field (no further precisions)	-	[19]
Beer brewing	2010 / Germany	FPCs: 169 m^2_{gr} Storage: 59 l/m^2_{gr}	15..70 to 80°C	- manual operator interference leading to unproper discharge of the solar heat storage - inappropriate manual control of a heat recovery unit reducing the amount of cold water to be heated by the STS - inappropriate minimum temperature threshold for discharging the solar heat storage - significantly higher than theoretical heat losses of the solar piping and the solar heat storage - undersized heat exchangers for the charge and discharge of the solar heat storage	Period: 1 year η_s (based on $Q_{sol,u}$): 27 % Achieved vs. planned η_s: -36 %	[6,7]
Cleaning / bottle flushing (food industry)	2010 / Germany	FPCs: 528 m^2_{ap} Storage: 76 l/m^2	Flow temperature: 60 to 70°C	- improper hydraulic connection of the solar heat storage with the buffer storage of the conventional heater - undesired charging of the solar heat storage by the conventional heater - unwanted mixing of the solar heat storage	-	[22]
Dairy processes	2012 / Switzerland	PTCs: 627 m^2_{ap} No additional solar heat storage	Flow temperature: 85 to 112°C depending on the process	- oversized solar collector field / necessity of a larger heat storage - high capacitive thermal losses especially at night - leakages at connection hoses - snow blocking the trackers in winter	Period: 6 years η_s (based on $Q_{sol,u}$ and beam solar radiation): 27 to 40 % depending on the year	[15]
Dairy processes	before 2013 / Switzerland	PTCs: 115 m^2_{ap} No additional solar heat storage	Flow temperature: 145°C	- high capacitive thermal losses especially at night - leakages at connection hoses - snow blocking the trackers in winter	Period: 2 years η_s (based on $Q_{sol,u}$ and beam solar radiation): 20 to 27 % depending on the year	[15]
Brick drying	2013 / Italy	LFCs: 2,640 m^2 No additional solar heat storage	-	- issue with the controller for the setpoint tracking and disturbance dissipation - difficulties to control the flow temperature of the solar collector field - minor unbalanced flow rates between the collector rows	-	[20,23,27]
Feed water pre-heating / hot water (meat industry)	2013 / Austria	FPCs: 1,067 m^2 Storage: 56 l/m^2	-	- strong fluctuations of the flow rate (and thus flow temperature) in the solar collector loop during the day	Period: 12 months η_s (based on $Q_{sol,u}$): 5 to 36 % depending on the month	[23,27]

(*continued on next page*)

Table 1 (*continued*)

Application	Installation year / country	Collector field / solar heat storage details	Process temperatures (return..flow)	Identified faults and problems	Performance analysis	Reference
Textile industry	2013 / Germany	PTCs: 70 kW_{th} Storage: varying volume from 10 to 70 m^3	-	-	Period: 1 year η_s (based on $Q_{sol,s}$): 27.8 %	[25]
Copper electrowinning	before 2014 / Chile	FPCs: 404 m^2 Storage: 62 l/m^2	Flow temperature: 50°C (unclear)	-	Period: 4 months η_s (based on $Q_{sol,u}$): 41 to 47 % depending on the month	[26]
Concrete element production / space heating	2014-2015 / Austria	FPCs: 1,411 m^2 Storage: 57 l/m^2 + 2,560 m^3 concrete (core activation)	20 to 70°C..26 to 90°C depending on the process	-	Period: 6 months (collector yield) / 9 months (f_s) Achieved vs. planned solar collector yield: +35 % Achieved vs. planned f_s: -27 %	[11]
Paint shop air heating / space heating	before 2016 / Austria	FPCs: 260 m^2 Storage: 54 l/m^2 + 3,300 m^2 soil storage	30 to 40°C..40 to 55°C depending on the process	- unwanted flows on the secondary side of the solar collector loop - higher than expected logarithmic mean temperature difference at the solar heat exchanger	Period: 4 months Achieved vs. planned η_s: +15 %	[10]
Gas pressure regulation (system D1 below)	2016 / Germany	FPCs: 421 m^2_{gr} Storage: 50 l/m^2_{gr}	30..50°C	- improper hydraulic configuration of the collector field leading to unwanted stagnation - leakages in the solar collector loop - undersizing of the solar heat exchanger - undersizing of the pumps of the solar collector loop - higher return temperature from the process than expected	Period: 3 years η_s (based on $Q_{sol,s}$): 35.4 % (one year only) f_s: 11 to 14.7 % depending on the year Achieved vs. planned solar collector yield: -16.6 to -25 %	[18,21]
Fruit drying and cooking / space heating / hot water	before 2017 / Austria	FPCs: 50 m^2 Storage: 140 l/m^2	-	- higher than expected heat losses of the solar heat storage	Period: 1 year Achieved vs. planned solar collector yield: +148 % Achieved vs. planned f_s: +19 %	[12]
Gas pressure regulation (system D8 below)	2019 / Germany	FPCs: 58 m^2_{gr} Storage: 104 l/m^2_{gr}	30..55°C	- faulty discharge of the solar heat storage - the auxiliary heater uses the solar heat storage but heats it more than necessary	Period: 1 year Achieved vs. planned solar collector yield: -40 %	[21]
Woodchip drying	before 2020 / Austria	FPCs (air): 219 m^2_{gr} No additional solar heat storage	-	-	Period: 1 year η_s: 51 % Achieved vs. planned η_s: -25 %	[13,14]
Woodchip and hay bale drying	before 2020 / Austria	FPCs (air): 115 m^2_{gr} Storage (rocks): 40 tons	-	-	Period: 1 year η_s: 51 %	[14]

tials. Some studies classify the faults according to the project phase to which they are related. The German Society for Solar Energy (Deutsche Gesellschaft für Sonnenenergie) [32] estimated that 45 % of the faults in STSs are linked to the planning phase, 39 % to the installation phase and 16 % to the operation phase. However, the methodology behind these figures is not specified. Olivier et al. [34] audited fifteen STSs for multi-family houses that were performing below expectations to identify the causes of the problems. They classified the identified faults according to the different project phases. For each system the suggested and implemented corrective measures are listed. Most studies dedicated to the evaluation of existing STSs, however, focus on the identification of common faults at component level or system part level. These are listed hereafter.

In Croy et al. [35], the results of an extensive monitoring program are published (projects *Solarthermie2000(plus)* and *ZIP*). The analysis of 60 large STSs (> 100 m^2) with 1..15 years of operation shows that about 25 % of the pumps had to be replaced. Many systems had issues with their heat exchangers: 12 out of 105 heat exchangers had to be replaced due to leakage or soiling, and approximately 10 % exhibited a significantly decreased performance. Leakage was also detected in approximately 20 % of the solar collector loops. Additionally, a large proportion (> 50 %) of the controllers of the STSs were defective, incorrectly parametrised, or exhibited wrongly connected sensors. Scheck et al. [36] checked in detail nine large STSs part of the *Solarthermie2000(plus)* project. Among other faults, defective pumps, improper volume flows, calcification or soiling of the heat exchangers, and problems with the collector temperature sensor are reported.

Within the *OPTISOL* project, ten STSs were investigated in multi-family houses in Austria with collector areas between 30 and 240 m^2 [37]. After optimisation, all STSs yielded over 350 kWh/m^2/a. In the analysis, 60 % of the STSs showed sub-optimally tuned or controlled volume flow rates in the solar collector loop. The integration and operation of the auxiliary heater was problematic for 60 % of the STSs and the volume kept at temperature in the solar heat storage was too large for 50 % of the systems. For 30 % the solar heat exchanger was too small or defective and 30 % exhibited defective or insufficient insulation of the storage and pipes.

The *COMBISOL* project also focused on the monitoring of 70 STSs for domestic hot water preparation and space heating in single-family houses in Austria, France, Germany and Sweden [38]. Here, no total system failure was found, but optimisation potential was identified for all systems. Generally, the authors report increased heat losses in almost every STSs. This concerned internal and external pipes, insulation of heat storages and heat storage connections, and missing siphons. Because of additional problems concerning the integration of the auxiliary heater and general installation faults, Thür et al. [38] advise to use prefabricated and standardised systems if possible. Breidler and Thür [39] focused on the 20 Austrian STSs part of the *COMBISOL* project and showed the most common faults in greater detail.

Sitzmann [40] investigated 60 STSs, principally for domestic applications. The author carried out a quality check of the systems one to three years after their installation. The quality is rated good for 28 systems, sufficient for 25 systems and poor for the remaining seven systems. Defective collector sensors and insufficient venting of the systems are identified as the most common critical defects, putting the systems out of operation. Other common deficiencies are the lack of a vessel to collect the solar fluid at the outlet of the blow-off line, insufficient insulation of the pipework, improperly laid sensor cables and inadequate system documentation.

Similarly, Fink et al. [41] examined and rated the quality of 120 STSs for commercial and domestic applications with collector areas from 20 to 400 m^2. 97 STSs were working well, 17 exhibited significant defects, and six were completely inoperative.

In a recent study, Darjay et al. [42] analysed in detail the faults in twelve solar water heating systems installed in Bhutan. The most common faults involved the plumbing, the solar collector and the absorber. Almost all systems had at least one fault in each of these three elements. Altogether, the systems surveyed appear to be in poor condition according to the number of failures reported.

Overall, while the observations vary slightly between publications, there is a common baseline regarding the reliability of STSs. In each study, a significant proportion of the investigated STSs required repairs or at least optimisation. Furthermore, a significant number of the faults identified are similar to those described for SHIP systems.

In addition to the analysis of existing systems other authors chose a different approach and carried out simulations to assess the impact of faults on the performance. This is the case in Rehman et al. [43] for the system efficiency and in Faure et al. [44] at component (collector) level.

3. Material and methods

3.1. Studied SHIP systems

The eight SHIP plants monitored in detail during the BEsoPro project are presented in Table 2. Pictures of the eight solar collector fields are shown in Fig. 1. The systems are applied in different industrial sectors with three different solar thermal collector technologies, namely ETCs, FPCs and CPCs. All plants use a liquid HTF in the solar collector loop, except one which is built with air collectors. The system sizes range from 58 m^2_{gr} to just above 1,000 m^2_{gr} with an average of 436 m^2_{gr} and a median of 334 m^2_{gr}. The flow temperature required by the processes is in the low-temperature range and varies between 40 and 85°C for the systems with a liquid HTF, up to 130°C for the system with air as HTF. The systems were built between 2012 and 2019 and data are therefore usually available over several years. Only the sensors foreseen by the system planners and installed from the start of operation are at disposal for monitoring. Temperature sensors, flow meters, heat meters, pyranometers, pressure sensors as well as control signals available on site are used for the evaluation of plant performance, but no additional measurement technology was installed for the purpose of the project. The data available for the eight plants have a measurement time step between ten seconds and 15 minutes, with a median of 90 seconds. Unless mentioned, no additional calibration of the existing sensors was carried out.

Besides the eight plants with detailed measurement data, the measured annual useful solar yield of five additional SHIP plants was available over several years. Details about these five systems are presented in Table 3. The systems were built between 2014 and 2016 and have an average collector area of 152 m^2_{gr} and a median of 136 m^2_{gr}. Two systems use air collectors. The flow temperature required by the processes varies from 45 to 70°C for the systems with a liquid HTF, up to 100°C for the systems with air as HTF. The measured annual useful solar yields were communicated to the agency in charge of the funding program, as it was mandatory to do so for systems larger than 100 m^2_{gr} built between August 2012 and the end of 2018 in Germany. Of the 27 systems in total only the five presented here delivered usable data.

Considering all 13 plants together, the average collector area amounts to 327 m^2_{gr} and the median to 191 m^2_{gr}. A graphical overview of the 13 systems is presented in Fig. 2.

3.2. Solar yield, solar radiation and pseudo solar utilisation ratio

For the 13 systems studied, a comparison is done between the annual solar yield estimated during the planning phase and the annual solar yield achieved.

Depending on the software used for the simulations, three different annual solar yields are reported in the simulation reports, namely the solar yield directly at the outlet of the collector field $Q_{sol,c}$, the solar yield delivered to the heat storage $Q_{sol,s}$ or the useful solar yield $Q_{sol,u}$. For a given system $Q_{sol,u}$ is lower than $Q_{sol,s}$, itself lower than $Q_{sol,c}$. $Q_{sol,s}$ is obtained from $Q_{sol,c}$ after subtraction of the heat losses from the piping and hydraulic components of the solar collector loop. Similarly,

Table 2
Overview of the eight monitored SHIP plants in the framework of the research project with detailed measurement data.

System	Application	Collector field / solar heat storage details	Process temperatures (return..flow)	Specific features of the plant	Range analysed data
D1	Gas pressure regulation	FPCs: 421 m^2_{gr} Storage: 50 l/m^2_{gr}	30..50°C	- SHIP plant combined with gas absorption heat pumps charging a common storage	Sep. 2017 – Apr. 2021
D2	Electroplating	CPCs: 297 m^2_{gr} Storage: 51 l/m^2_{gr}	Flow temperature: 65 to 75°C depending on the process	- water as HTF with active anti-freeze protection in winter - direct connection between collector field, storage and energy sinks (no heat exchanger in-between) - additional minor consumers: heating registers for space heating (flow process temperatures: 45 to 65°C, depending on the register)	Jan. 2017 – Dec. 2020
D3	Bitumen processing	FPCs: 191 m^2_{gr} Storage: 131 l/m^2_{gr}	10..50 to 70°C	- additional minor consumers: feed water pre-heating for a steam boiler (process temperatures: 10..90°C) and space heating in winter (flow process temperature: 60°C)	Jan. 2016 – Dec. 2018; Jan 2020 – Dec. 2020
D4	Car washing	CPCs: 371 m^2_{gr} Storage: 8 l/m^2_{gr}	30..85°C	- water as HTF with active anti-freeze protection in winter - the solar heat storage serves as hydraulic separator - additional consumer: pre-heating of osmosis water	Aug. 2018 – Dec. 2020
D5	Drying processes (pharma industry)	ETCs: 183 m^2_{gr} No heat storage	Flow temperature: < 130°C	- air collectors, pre-heating outdoor air - no heat storage	Jan. 2019 – Jun. 2021
D6	Vegetable farming	FPCs: 961 m^2_{gr} Storage: 44 l/m^2_{gr}	25..40 to 70°C depending on the process	- two different processes: air dehumidification and air heating for greenhouses - additional minor consumer: pre-heating of irrigation water	Aug. 2019 – Dec. 2020
D7	Beer brewing	ETCs: 1,007 m^2_{gr} Storage: 50 l/m^2_{gr}	Flow temperature: 80 to 85°C	- collectors mounted partly on the roof and partly on the façade	Jun. 2020 – Jun. 2021
D8	Gas pressure regulation	FPCs: 58 m^2_{gr} Storage: 104 l/m^2_{gr}	30..55°C	- SHIP plant combined with a micro combined heat and power unit charging a common storage	Sep. 2019 – Jun. 2021

Table 3
Overview of the five monitored SHIP plants in the framework of the research project with measured data of the annual solar yield.

System	Application	Collector field / solar heat storage details	Process temperatures (return..flow)	Specific features of the plant	Range analysed data
U1	Car washing	FPCs: 131 m^2_{gr} Storage: 38 l/m^2_{gr}	10..45°C	- additional to water pre-heating for car washing, the solar heat is also used in winter to keep the washing bays ice-free through concrete core temperature control (flow process temperature: 25 to 35°C)	Jan. 2015 – Dec. 2019
U2	Woodchip drying	FPCs: 136 m^2_{gr} No heat storage	Flow temperature: < 100°C	- air collectors, pre-heating outdoor air	Jan. 2015 – Dec. 2020
U3	Woodchip drying / Animal feed drying	ETCs: 186 m^2_{gr} Storage: 27 l/m^2_{gr}	45..80°C	- air collectors - additionally, the system supplies heat for a heating network in winter (process temperatures: 50..85°C) - water heat storage connected to the collector field with an air-to-water heat exchanger	Jan. 2016 – Dec. 2020
U4	Liquid container cleaning	FPCs: 101 m^2_{gr} Storage: 40 l/m^2_{gr}	10..60°C		Jan. 2016 – Dec. 2020
U5	Vehicle cleaning	CPCs: 206 m^2_{gr} Storage: 39 l/m^2_{gr}	30..70°C		Jul. 2016 – Jun. 2017

$Q_{sol,u}$ is obtained from $Q_{sol,s}$ after subtraction of the heat losses from the heat storage and the piping and hydraulic components between the heat storage and the connection point to the supplied process. Depending on the hydraulic configuration of the system experience shows that the difference between $Q_{sol,c}$ and $Q_{sol,u}$ amounts to a few percent for medium to large SHIP systems as the ones studied here.

Similarly, depending on the system, the solar yield is measured at three different locations in the hydraulic system, depending on the position of the heat meter. The three possible locations correspond to the same three locations as for the simulated yields. Unfortunately, as no additional measuring device was installed for the purpose of this study, the location of the simulated solar yield and the measured solar yield are not necessarily identical for a given system. This is specified in the presentation of the results.

Concerning the measured solar yield, only full years of data, from January to December are considered. For two systems it was not possible to get a full year of data, however sufficient data are available for one year, not starting from January. In this case, the first month of available data is taken as start date. Ten systems have more than one year of data available. For these systems only the year(s) corresponding to the median of the measured solar yield is/are considered. More precisely, for systems with an odd number of measured years the solar yield is taken for the year corresponding to the median. For systems with an even number of measured years the solar yield is taken as the mean of the two years corresponding to the two middle values.

The annual global horizontal solar radiation considered in the simulations is also compared to the measured annual global horizontal solar radiation. Concerning the measured values, the year(s) considered correspond(s) to the year(s) selected with the median for the measured solar yield. The measured values considered are open-access data provided by the German Meteorological Service (DWD) [45]. The data given in [45] are generated for any locations in Germany from ground measurements and satellite data with a spatial resolution of 1 km x 1 km. Concerning the horizontal solar radiation used in the simulations, data are available for all systems from the simulation reports except for the system U2. In this particular case, the average annual global solar radiation over the period 1991-2010 given in [45] is used instead. This is a

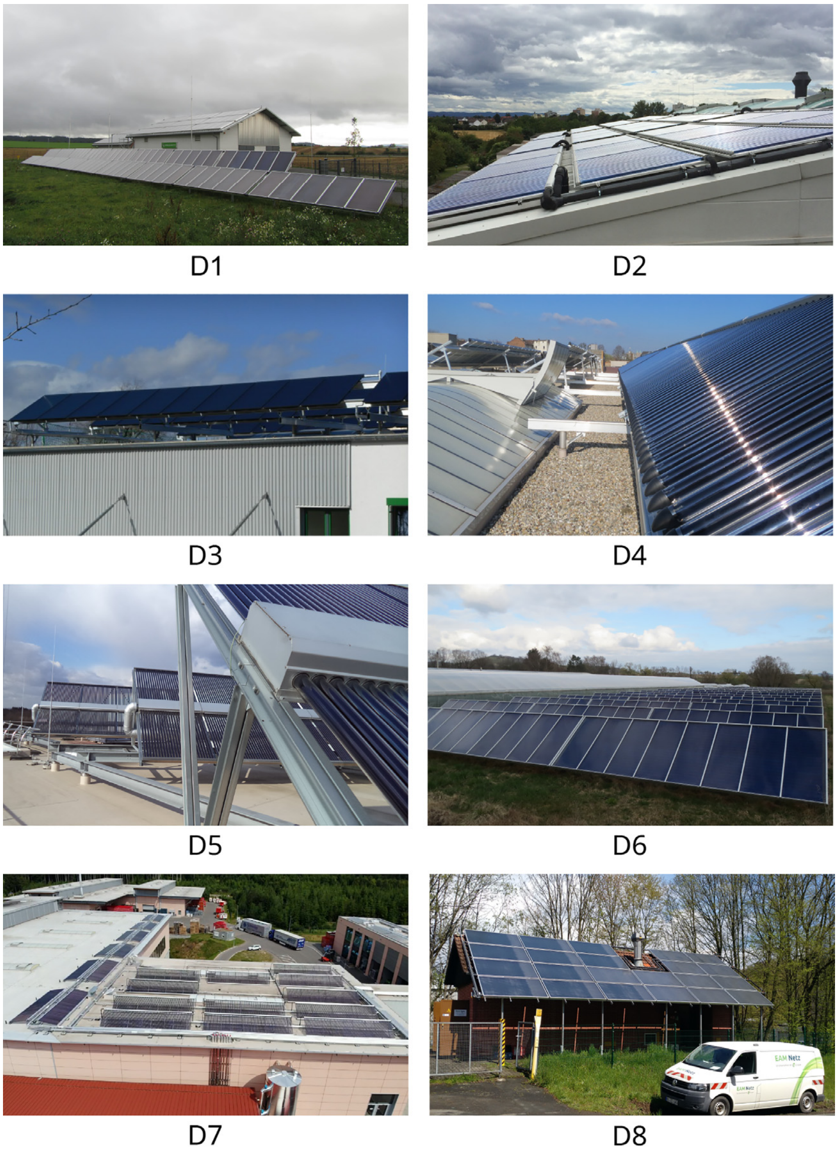

Fig. 1. Pictures of the solar collector fields of the eight monitored SHIP plants with detailed measurement data.

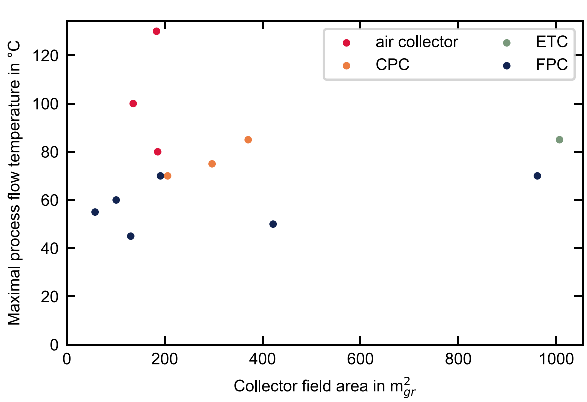

Fig. 2. Graphical overview of the 13 systems studied, presented with their maximal process flow temperature of the main processes as a function of the gross collector field area. Each colour indicates a different collector technology.

reasonable value as simulation software usually uses long-term meteorological trends, averaged over several years, for its calculations.

A pseudo annual solar utilisation ratio η_s is also calculated for each system as defined in Eq. 1, where Q_{sol} is the annual solar collector yield and H the annual global horizontal solar radiation as the total solar radiation in the collector plane is unknown.

$$\eta_s = \frac{Q_{sol}}{H} \tag{1}$$

3.3. Evaluation of the measurement uncertainty

The measurement uncertainties of the solar yield and solar radiation are estimated. For the solar yield, the specifications of the sensors installed in each system are unfortunately unknown. The estimated uncertainty is therefore derived from plausible data from the literature, with a distinction between systems with a liquid as HTF and systems with air as HTF.

For systems using a liquid as HTF, it is assumed that the solar yield is measured with commonly used heat meters. The measurement uncertainty of heat meters is given in DIN EN 1434-1 [46]. Conservatively assuming a heat meter of class 3 and reasonable assumptions for the parameters in [46], a maximal measurement error of ± 5.5 % for the measured thermal energy is estimated. Assuming a uniform distribution,

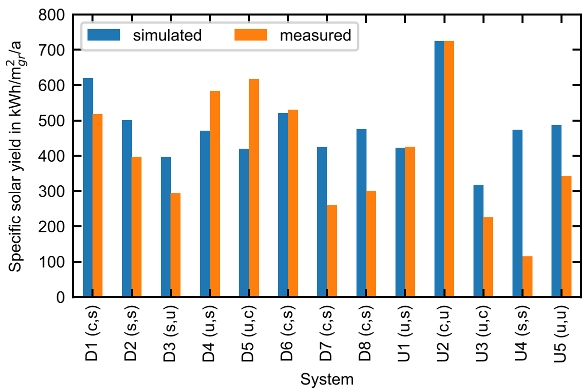

Fig. 3. Planned and measured – for the year(s) corresponding to the median – specific annual solar yields of the 13 systems studied.

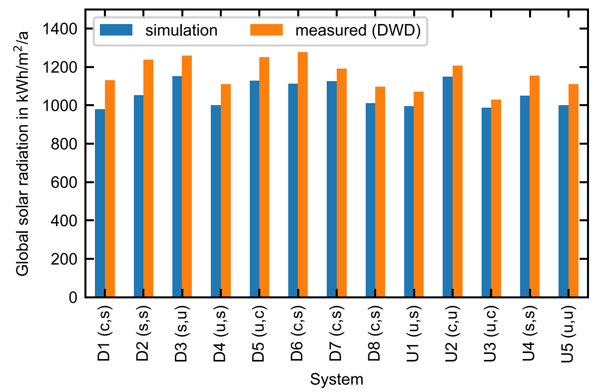

Fig. 4. Measured annual global solar radiation from the DWD data – for the year(s) corresponding to the median – and annual global solar radiation used in the simulations of the 13 systems studied.

this corresponds to a standard measurement uncertainty of 3.2 % of the annual solar yield for systems with a liquid as HTF.

No similar standard to DIN EN 1434-1 exists for heat flow measurements with air as HTF. Instead the norm DIN EN 12599 [47], dealing with measurements in air handling units in the building sector is taken as reference for the following. The permissible measurement uncertainties of the air volume flow rate (± 10 % of the measured value), and the air temperatures (± 2 K) given in the norm are considered as maximal measurement errors, and the standard uncertainty derived assuming a uniform distribution. Concerning the product of air density and specific heat capacity, a standard uncertainty of 5 % is assumed. Assuming a 150 m^2 collector field (nominal thermal capacity of 105 kW) and a temperature difference of 60 K between collector field inlet and outlet, a standard measurement uncertainty of 8 % of the annual solar yield for systems using air as HTF is estimated.

For solar radiation, the DWD mentions a mean uncertainty of 6 % of the generated gridded data [48]. This value is thus taken as standard measurement uncertainty for the measured annual global solar radiation in the following.

3.4. Selection of common faults and problems

Two approaches are combined to identify common faults and problems that might occur in large-scale SHIP plants. For about a decade, there has been a specific support scheme for SHIP plants in Germany. To obtain the investment grant, SHIP plant planners must fill in an application with technical details. Authors of this paper have been advising the funding agency for several years, especially on the technical aspects of the projects submitted. In doing so, advice could be given on identified issues, thus avoiding them at an early stage of the project. The present study builds on this practical experience acquired over the years, for which a preliminary analysis was previously summarised in Ritter et al. [49]. The experience gained with the advisory activity is complemented by the detailed analysis of measurement data of the plants presented in Table 2 and Table 3. A list of the ten most common faults and problems is compiled based on these two sources of information.

4. Results

4.1. Solar yield, solar radiation and pseudo solar utilisation ratio

The comparison between the planned and measured specific annual solar yields as described in Section 3.2 is presented in Fig. 3. The 13 systems are presented with a specific coding. The eight systems with detailed measurement data are indicated with the letter D, the five others with the letter U. In brackets is indicated where the planned (first value) and the measured (second value) solar yields are determined respectively, namely at the outlet of the collector field (c), delivered to the heat storage (s) or the useful solar yield (u). In general, no other relevant information is available on the exact positions and characteristics of the sensors used to calculate the solar yields. When available, additional information relevant for the comparison of the planned and measured values presented in Fig. 3 is listed in Table 4.

The results show that most of the systems (eight) achieve solar yields significantly lower than predicted, ranging from -16 % for system D1 to -76 % for system U4. Three systems (D6, U1 and U2) reach the expectations, while for systems D4 and D5 the measured solar yields largely exceed the simulated ones.

The annual solar yield depends on several factors, notably the temperature of the supplied processes and the profile of the heat demand as well as the available solar radiation. If these parameters differ from the values considered during system planning, this has an impact, sometimes significant, on the solar yield achieved. It is therefore important to assess these parameters. Concerning the load profiles, not enough measurement data are available at the 13 plants for comparison with the values given in the simulation reports. However, it can be expected that if the roof area is not a limiting factor, the solar heating plants are designed to meet the summer heat demand, as this is a usual design strategy for SHIP plants [3]. For solar radiation the comparison between simulation and measurement as described in Section 3.2 is presented in Fig. 4. For system U2, long-term radiation data from the DWD are taken as no value is given in the simulation report.

Interestingly, the annual global radiation measured by the DWD follows the trend of the radiation used in the simulations but exceeds it in all cases, on average by 10.0 ± 4.0 %, with a minimum of 4.4 % (system U3) and a maximum of 17.5 % (system D2). This is probably caused by the use of long-term time series in the simulations which underestimate current radiation levels as important variations of the surface solar radiation have been observed over the past decades. This effect is called global dimming and brightening and is widely acknowledged in the literature [50].

The planned and achieved pseudo annual solar utilisation ratios (see Section 3.2) are also compared. The results are presented in Fig. 5 as the ratio between both pseudo solar utilisation ratios. The estimated expanded uncertainty (2σ) calculated according to Section 3.3 is also shown. It should be stressed again that for a given system the location of the measured solar yield does not necessarily correspond to the location of the simulated solar yield, adding additional uncertainty not estimated in the figure. Eleven of the 13 systems have a lower than planned pseudo solar utilisation ratio, ranging from -5 % (system U2) to -78 % (system U4). Two systems exceed the expectations by 12 % (system D4) and 33 % (system D5). Considering the uncertainty of the measurements, seven systems (D1, D2, D7, D8, U3, U4 and U5) perform worse, and four systems (D4, D6, U1 and U2) perform within the

Table 4
Available additional information relevant for the comparison of the planned and measured values presented in Fig. 3.

System	Comments
D2	The measured temperatures and flow rate for the calculation of the solar yield are corrected with correction factors determined from short-term on-site measurements with non-invasive sensors, as the raw data were not plausible.
D3	The measured useful collector yield is a lower bound, as the hydraulic configuration allows heat extraction directly on the primary side of the solar collector loop for pre-heating of the processed material in the spring after winter. This energy stream is not measured.
D4	The measured $Q_{sol,s}$ is close to $Q_{sol,u}$ regarding the hydraulic configuration.
D5	There must be an important, non-quantifiable difference between the measured collector yield and the useful collector yield (not measured). There is indeed a direct hydraulic connection between the collector field flow and return ducts. When the flow rate required by the process is lower than the (constant) flow rate supplied by the fan in the solar collector loop, part of the collector outlet stream is mixed with the inlet stream. As the solar yield is measured between the collector field inlet and outlet, the flow recirculated through the collector field also contributes to the measured solar yield, despite increasing the system losses and not contributing to the useful solar yield.
U2	The measured $Q_{sol,u}$ is close to $Q_{sol,c}$ regarding the hydraulic configuration.
U3	The measured $Q_{sol,c}$ is close to $Q_{sol,u}$ regarding the hydraulic configuration.

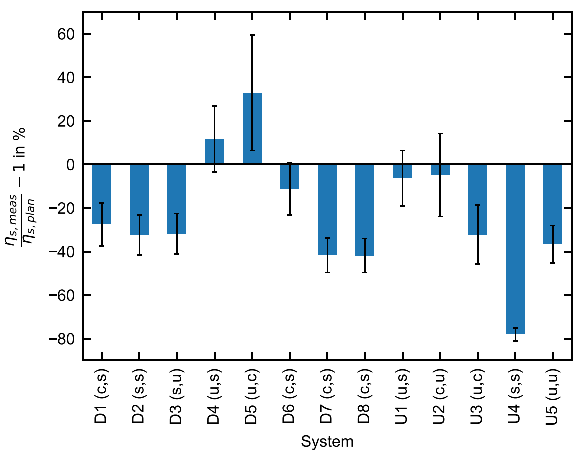

Fig. 5. Ratio of the measured and planned pseudo annual solar utilisation ratios as well as estimated expanded uncertainty (2σ) of the 13 systems studied.

expected range with as a high certainty. Due to the measurement problems encountered for the systems D3 and D5 (see Table 4), the actual measurement uncertainty on the solar yield is non-quantifiably higher than the one used to calculate the expanded uncertainty shown in Fig. 5. For this reason, no final quantitative assessment can be made for these two systems.

4.2. Detected faults and problems in the eight systems with detailed measurement data

The analysis of the detailed monitoring data provides explanations for the observed differences between measured and estimated pseudo solar utilisation ratios, although some aspects may remain unnoticed due to data unavailability. The five systems with significantly lower than expected pseudo solar utilisation ratios are presented first (D1, D2, D3, D7 and D8).

Several problems are identified in system D1. First, an undersizing of the solar heat exchanger is found, leading to a much higher than expected logarithmic mean temperature difference (LMTD). The design mass flow rate is not achieved in all sub-collector fields, indicating poor design of the solar collector loop hydraulics. Also, an inappropriate connection of parts of the collector rows is discovered. All collector rows are indeed connected on the same side to the flow and return distribution pipes, which, with the collector type used in system D1, is not a problem for short rows with five collectors in series. For longer rows with eight and nine collectors in series, an uneven flow distribution across the collector rows is identified. These flaws result in higher than expected collector temperatures and stagnation of the collector field, starting although the solar heat storage is not fully charged. As an additional problem, leakages are noticed in some collector rows.

For system D2, higher than expected return temperatures to the collector field are identified. They are caused on the one hand by improper temperature stratification in the storage tank, as the tank is partly mixed during charging and discharging. On the other hand, the process with the lowest return temperature is not active in summer. The setpoint of the temperature delivered by the collector field in the solar heat storage is higher than required by the processes and even 10 K higher than the setpoint temperature of the auxiliary heater, which leads to further inefficiencies. In addition, the temperature measurements in the collector field indicate an uneven flow distribution in the collector rows.

In system D3, an undersizing of the solar heat exchanger is identified as well as unbalanced capacity flows between the primary and secondary side of the heat exchanger which leads to higher than necessary collector temperatures. Similarly, the heat exchanger discharging the solar heat storage is undersized as well as the pump on its primary side, due to an underestimation of the peak load. Consequently, the pseudo annual solar utilisation ratio is lower than expected, even though this assessment should be considered with caution as the solar yield delivered to one of the processes is not measured (see Table 4).

For system D7, the simplification of the system simulations, including not considering the different orientations of the collector fields, not taking into account shading effects as well as ignoring the typical snow cover in winter at the plant location, leads to an overestimation of the collector yield. Similarly to system D3, the solar heat exchanger is undersized and the capacity flow between the primary and secondary side is unbalanced. An undersizing of the pump of one of the sub-collector fields is also identified.

For system D8, shades on the collector field caused by the surroundings especially in the morning and in winter are not considered in the simulations. Additionally, the solar heat storage is kept at a higher temperature than necessary due to non-optimal connection and control of other heat supply technologies that also charge the solar heat storage.

Two systems show measured pseudo solar utilisation ratios in the range of forecasted values. Concerning system D6, this result is confirmed by the fact that no significant issues could be identified during the analysis of the detailed measurement data.

For system D4, no serious problems are identified, apart from a malfunctioning pulse transmitter causing sporadic shutdowns of the solar pump. The problem disappeared after replacement of the faulty device. Communication with the planner further reveals that conservative assumptions were made for the simulations. Notably, even though it was assumed that a minimum flow temperature of the solar heat must be reached to be used in the process, in the real plant the solar heat is used in the process as pre-heating even if the threshold is not exceeded. Despite this fact a good agreement is found between measured and planned pseudo solar utilisation ratios.

The last system D5 appears to have a higher pseudo solar utilisation ratio than planned. On the one hand, very conservative assumptions were considered for the estimation of the solar yield. A relatively high and constant setpoint collector flow temperature was especially con-

Table 5
Overview of the ten most common faults and problems identified in SHIP plants.

ID	Fault / Problem	Consequences
F1	One-sided connection of a collector row regardless of the maximum allowed number of collectors in series in the row	Reduction of the solar collector field efficiency by high collector temperatures; stagnation at the end of the collector row and risk of spreading to the entire row
F2	Uneven specific flow rate through the collector rows	Reduction of the solar collector field efficiency; risk of partial stagnation in summer
F3	Leakages in the solar collector loop	Stagnation when the pressure in the solar collector loop drops below a certain level
F4	Undersizing of the pump(s) in the solar collector loop	Reduction of the solar collector field efficiency by high collector temperatures; earlier stagnation
F5	Undersizing of the solar collector loop heat exchanger	Reduction of the solar collector field efficiency by high collector temperatures; earlier stagnation; setpoint temperatures are not reached
F6	Unbalanced capacity flows at the solar collector loop heat exchanger	Reduction of the solar collector field efficiency by high collector temperatures; earlier stagnation; setpoint temperatures are not reached
F7	Total heat storage volume achieved through interconnection of several smaller heat storages	High storage heat losses; higher risk of storage mixing and unbalanced (dis-) charging
F8	Improper preparation of the heat transfer fluid	Reduction of the solar collector field efficiency; earlier stagnation; setpoint temperatures are not reached
F9	Unsuitable connection or control strategy of the auxiliary heating unit(s) connected to the solar heat storage	Reduction of the storage capacity available for the STS; reduction of the collector field efficiency; earlier stagnation
F10	Insufficient data about the heat sink(s) during the planning phase	Wrong dimensioning of the solar collector field and other components of the SHIP plant; by oversizing, the specific solar yield can be significantly lower than expected

sidered in the simulations, whereas in the real plant the flow rate in the collector loop is constant, resulting in a variable collector flow temperature. On the other hand, the available data reveal an uneven flow distribution between the different collector rows, as well as a problematic uncontrolled mixing of part of the collector outlet stream with the collector inlet stream, as detailed in Table 4. Because of the latter, the higher than planned pseudo solar utilisation ratio measured should be considered with caution.

4.3. Ten most common faults and problems in SHIP plants

During the scientific support of the German funding program for SHIP, a high number of solar heating plants planning documents have been reviewed and obvious planning errors could be avoided at an early stage. In combination with the experience gained from the detailed monitoring of the plants, a list of the ten most common faults and problems identified is elaborated and summarised in Table 5. Further details are presented in the following. Interestingly most of the faults and problems identified (F2, F3, F4, F5, F9 and F10) are mentioned in previous studies listed in Section 2.1.

In some of the systems studied, an uneven flow distribution is detected along some collector rows. The main cause identified is a one-sided connection of the affected collector rows without respecting the maximum allowed number of collectors to connect in series with a one-sided connection (F1). This results in a non-uniform flow distribution along the collector row, as the flow through the collectors decreases with increasing distance from the connection. This leads to different collector temperatures along the row and possibly to stagnation in the last collectors of the row even with moderate irradiance. This results in stagnation of the entire row or even the complete collector field with a certain delay. Even if stagnation can be avoided, the efficiency of the last collectors in the row is decreased if the heat transfer is reduced due to a non-turbulent flow regime because of the reduced velocity. For this reason, it is important not to exceed the maximum number of collectors specified by the manufacturer when connecting the rows on one side. If the collectors are connected on both sides, the manufacturer's specifications must be considered too but this generally causes fewer problems; if necessary, the row must be divided into several rows with fewer collectors in series to ensure fault-free operation.

In a few systems, an uneven specific flow rate is detected between the different collector rows (F2). This leads to different outlet temperatures at the end of the rows. This results in unnecessarily high temperatures in the collector rows with the weakest specific flow rate, which increases the thermal losses. In addition, stagnation may occur in these rows in summer at medium and high irradiance, which can spread to the entire collector field. This results in situations in which it comes to stagnation in parts of the collector field or even in the entire field, even though storage capacity is available, or a sufficiently large heat demand is present on the process side. Therefore, intensive care should be taken during installation to ensure a uniform and sufficient specific flow rate. This can be achieved either by means of balancing valves, which have the advantage that they can also be readjusted during operation, or by means of a proper hydraulic design that ensures identical pressure losses over each collector row (so-called Tichelmann principle). This last technique, however, usually requires a more complex piping system. The issue does not only apply to systems with a liquid HTF but also with air, although stagnation is not a problem with the latter.

In some cases, leakages occurred at screw connections in the piping of the solar circuit (F3). The loss of solar fluid causes a drop in system pressure, which can lead to a complete standstill of the system without intervention. There are three usual potential reasons for leaks in the solar collector loop, namely (a) insufficient temperature resistance of the gaskets used, (b) tension at the screw connections due to unsuitable installation of the pipes or (c) over-tightening of the screw connections, damaging the gaskets. Care should therefore be taken during installation to use gaskets that can withstand the temperatures to be expected in regular operation (continuous load) as well as during stagnation of the system (temporary load). In addition, care must be taken during installation to ensure that the pipes are laid without tension and that the screw tightening torque is appropriate. The effect of a leakage in a solar collector loop is exemplified in Fig. 6. The pressure is measured on the primary side of the solar collector loop before the pumps. The daily drops observed are expected and correspond to the operation of the solar pumps. On the 21st of August, it can be noticed that the pressure does not return to its initial level in the evening and the level of the nightly plateau keeps decreasing over the week, highlighting a leakage. Due to the pressure reduction, the pump of the upper collector field can no longer circulate the fluid, causing stagnation of the field during the following days, as indicated by the high temperatures reached in the flow pipe of the upper field. The pump of the lower collector field kept functioning properly. After repairing the leak and restoring the initial pressure level the pump of the upper field restarted its normal functioning (not shown in the figure).

The undersizing of the pump(s) in the solar collector loop (F4) is caused by an underestimation of the pressure losses in the loop and results in a lower than targeted volume flow rate in the solar collector loop, or in sub-collector loops, e.g. when sub-collector fields are supplied by individual pumps. This problem occurs frequently and is mostly identified in the primary solar collector loop. Therefore, the mean collector temperature is unnecessarily higher than planned and heat losses are

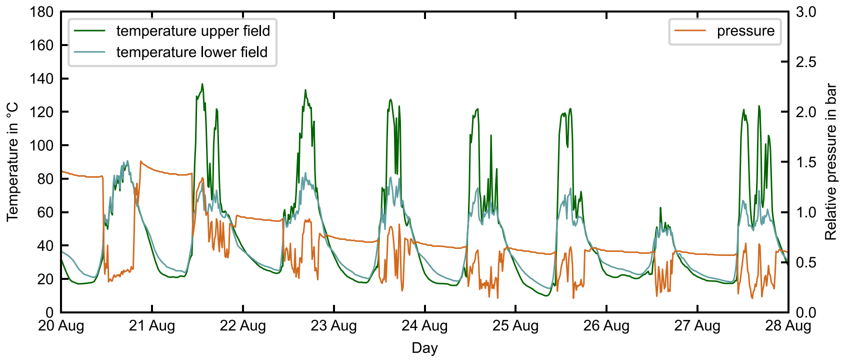

Fig. 6. Measured collector fields flow temperatures and primary solar collector loop pressure (above atmospheric pressure) before the pumps, averaged over 15 minutes of system D1.

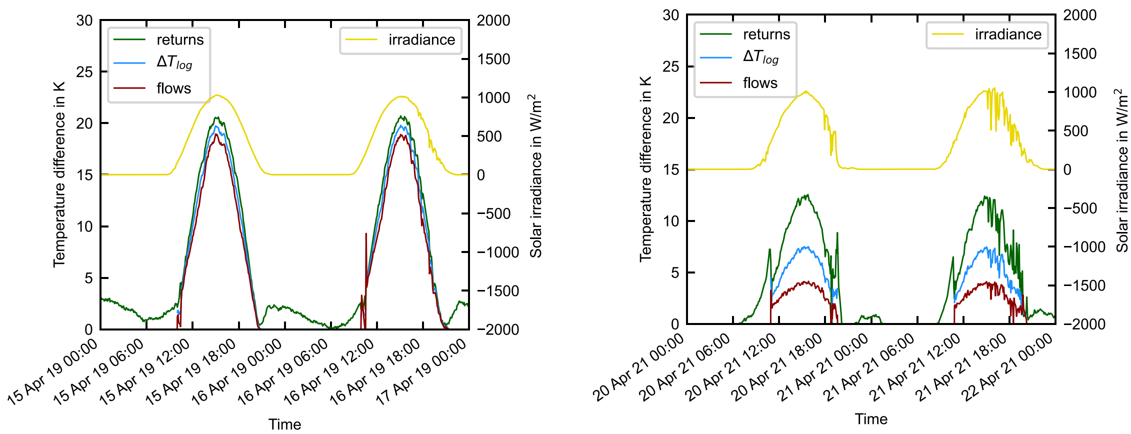

Fig. 7. Measured LMTDs and temperature differences between the flow temperatures and the return temperatures averaged over five minutes on both side of the solar plate heat exchanger as well as solar irradiance of system D1, before (left) and after (right) replacement of the heat exchanger.

increased. In most unfortunate cases, the maximum permissible temperature in the solar collector loop is exceeded, resulting in system stagnation and usually no solar output for the rest of the day, whereas higher flow rates would have delayed this effect or avoided it altogether. Due to the considerable negative influence this fault can have on the solar yield, special care is needed when calculating the pressure losses and selecting a suitable pump. To be able to re-adjust the flow rate, if necessary, the selected pump(s) should preferably have a certain reserve.

The undersizing of the heat exchanger separating the primary and secondary solar collector loops (F5) leads to a high LMTD which should not exceed 5 K by proper dimensioning, for an external water-to-water heat exchanger. This fault is frequent and can have different origins. The dimensioning of the heat exchanger itself, but also the installation of a heat exchanger that deviates from the planning or an incorrect installation (interchanging the connections) are potential reasons. Consequently, the temperature in the solar collector loop is increased unnecessarily, leading to a lower solar yield. In addition, the flow temperature on the secondary side can be significantly lower than planned with an undersized heat exchanger. This is specially a problem if the control is based on reaching a setpoint temperature for the process, in which case heat at a temperature below the threshold will not be supplied to the process and therefore the useful solar yield further reduced.

An example is shown in Fig. 7 for the solar heat exchanger of system D1. The LMTD as well as the difference between the return and flow temperatures on both sides of the heat exchanger are displayed over two days. Before replacement of the heat exchanger (Fig. 7, left), the LMTD reaches up to 20 K. After replacement (Fig. 7, right) the situation notably improved with a maximum near 7.5 K. Two consecutive sunny days are chosen at two very similar period of the year (mid-April 2019 and mid-April 2021) for comparison. Despite slightly differing evolution patterns of the secondary return temperature (Fig. 8) between both periods compared, a significant reduction of both temperatures on the primary side after replacement of the solar heat exchanger can be observed. In addition, the difference between the return temperatures is much higher than the one between the flow temperatures (Fig. 7, right), which is caused by an unbalanced capacity flow between the primary and secondary sides (see Fig. 9).

To avoid undersizing the heat exchanger, it should be dimensioned with a specific transmission capacity of 120 $W/K/m^2_{gr}$, which corresponds to a specific nominal output of the collector field of 600 W/m^2_{gr} collector area [3]. This recommendation applies to external plate heat exchangers, which are standard in large solar thermal systems, especially in SHIP systems.

Another identified problem, related to the solar heat exchanger and the pumps, with a significant influence on the efficiency of the system, is an imbalance between capacity flows on both sides of the solar collector loop heat exchanger (F6). Regarding the consequences, a distinction must be made between case (a) where the capacity flow on the primary side is higher than on the secondary side of the solar collector loop heat exchanger and case (b) where the capacity flow on the secondary side is higher than on the primary side. In case (a), the return temperature of the primary side cannot be cooled sufficiently, which causes an increase in the mean collector temperature and thus an increase of the thermal losses. In case (b), the difference between the primary and secondary side flow temperatures increases. Depending on the control strategy, either the setpoint temperature for loading the heat storage is not reached or the flow temperature on the primary side is unnecessarily high to ensure the desired flow temperature on the secondary side. In both cases, the LMTD of the solar heat exchanger rises. Generally, it is desirable that the ratio of the two capacity flows (primary and secondary side) is as close as possible to 1.

The problem is exemplified in Fig. 9. The specific capacity flow is shown over two days on both sides of the solar heat exchanger. The specific capacity flow corresponding to the plateau amounts to

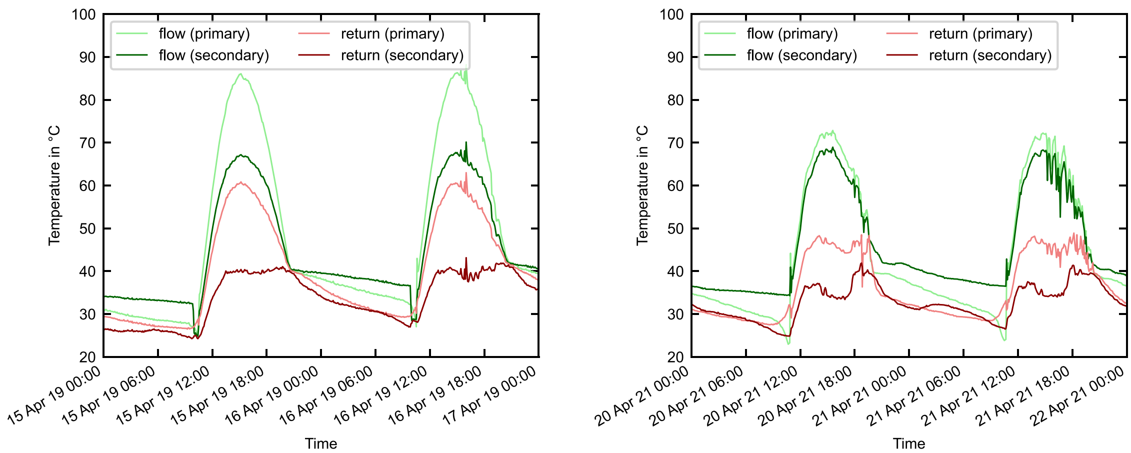

Fig. 8. Measured temperatures averaged over five minutes on the primary and secondary sides of the solar plate heat exchanger of system D1, before (left) and after (right) replacement of the heat exchanger.

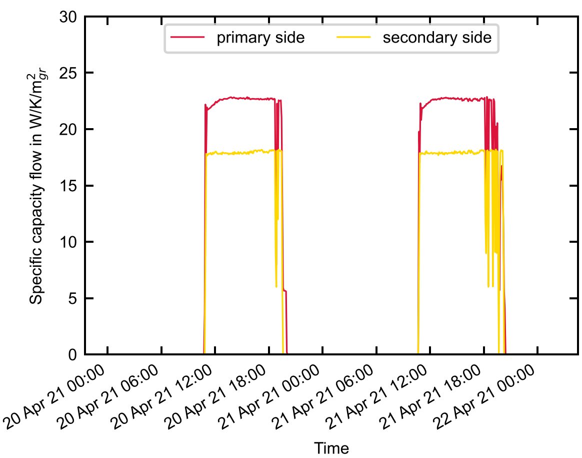

Fig. 9. Measured specific capacity flows averaged over five minutes on the primary and secondary sides of the solar plate heat exchanger of system D1.

22.7 $W/K/m^2_{gr}$ on the primary side and 17.9 $W/K/m^2_{gr}$ on the secondary side, i.e. 21 % lower than it should be to reach an equal capacity flow. This corresponds to case (a) and as depicted in Fig. 8 (right) the return temperature on the primary side is not sufficiently cooled down. A further increase of the flow rate on the secondary side of the heat exchanger was however not possible without replacement of the pump.

For several reasons, the total heat storage volume is sometimes achieved by interconnecting several smaller heat storages (F7). In the planning phase the interconnection of several very small storage tanks (0.5 m^3 or 1 m^3) could be identified several times, up to 14 in one unprecedented case. In most cases, the use of several storage tanks was not linked to space constraints but to the availability of components in the supplier's standard portfolio. Many negative practical experiences with interconnected storage volumes (mainly in parallel, but also in series) have been reported, in Peuser et al. [51] and Schramm and Adam [22] for instance. Generally, several heat storages increase the heat losses compared to a single large heat storage as the surface of exchange with the surroundings is increased. In addition, the use of several interconnected heat storages increases the risk of tank mixing which disturbs the thermal stratification and consequently reduces the useful solar yield. During the commissioning of systems with parallel heat storages, the flow through the storages is balanced by means of valves. With time this balance is typically lost due to limescale, deposits, or other effects that change the pressure losses in the storage loops. In the worst case, not all heat storages are used. Thus, the installation of a single large storage tank is recommended [3,52]. The VDI 3988 guideline also stipulates that under no circumstances, more than two parallel or three serially connected storages should be installed [3]. If it is not possible to realise the required storage volume with this recommendation inside the building, the installation of a single storage tank outside the building should be examined.

A rapid decrease in the transmission capacity of a heat exchanger, may be due to an improper treatment of the fluids used in the hydraulic circuits (F8). The lack of treatment leads to heat exchanger fouling, especially by limescale. The reduction of the transmission capacity results in a higher LMTD across the corresponding heat exchanger and thus an unnecessary increase of the temperatures in the system, causing additional thermal losses. Besides, fouling causes increased pressure losses in the affected components and thus an increase of the required pumping power. It is therefore important to follow the manufacturer's instructions for the preparation of the fluids used when filling the hydraulic circuits. It is also highly recommended to install shut-off valves on the primary and secondary side of each heat exchanger, both in the flow and return pipes, to be able to remove and flush the heat exchanger with little effort, which can help restore the original transmission capacity. This is particularly important for the heat exchanger connecting the heat sink when the process requires fresh water heating, as treatment is usually not an option in this case.

The auxiliary heating unit(s) can be a source of inefficiencies for the STS. An unsuitable control strategy or improper hydraulic connection of another heat generator to the solar storage tank (F9), increases the temperatures in the system, leading to a large increase in heat losses and inefficient operation of the solar thermal collectors. In addition, it may cause regular stagnation periods, especially during the summer months, if the storage tank is significantly charged by the auxiliary heater. This was the case for system D8, where the solar collector field and the auxiliary heater are connected to the same heat storage in parallel. The auxiliary heating unit initially heated the (solar) storage to a permanently high temperature as illustrated in Fig. 10. Between July and the end of December 2020, except for September when the auxiliary unit was shut down, the complete heat storage remains at a high temperature. In January 2021 a temperature limitation was introduced so that the auxiliary heater only charges the upper part of the heat storage, significantly reducing the temperatures in the storage. The effect on the solar yield for different control strategies of the auxiliary heater for this example is illustrated in Fig. 11. In the initial situation (green) no limitation was set for the auxiliary heater on the maximum share of the storage that is heated, which led to a warmer than necessary heat storage not only at the top but also at the lower levels of the storage. After introduction of the temperature limitation for the auxiliary heater (red) the daily so-

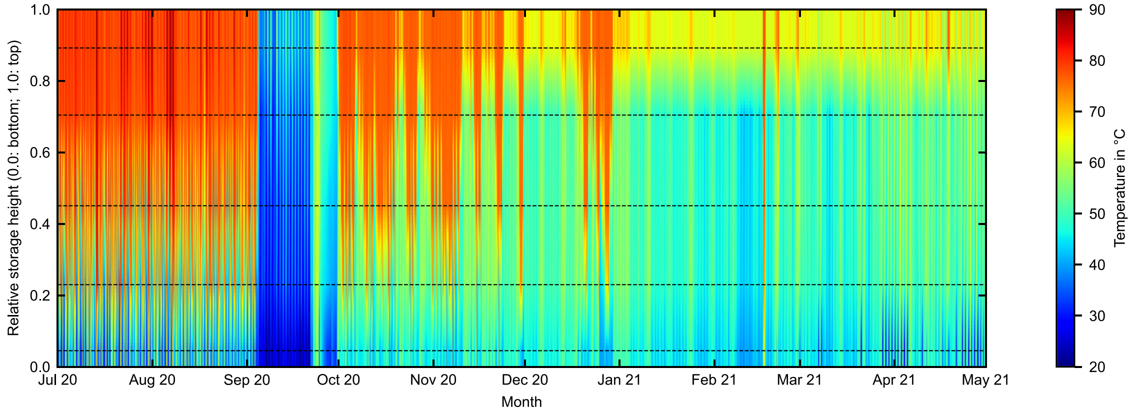

Fig. 10. Measured storage temperatures in the storage height averaged over 30 minutes of system D8. The five dashed lines show the position of the temperature sensors. Between the sensors the temperature is linearly interpolated. Below the lower sensor and above the upper sensor the temperatures are considered constant.

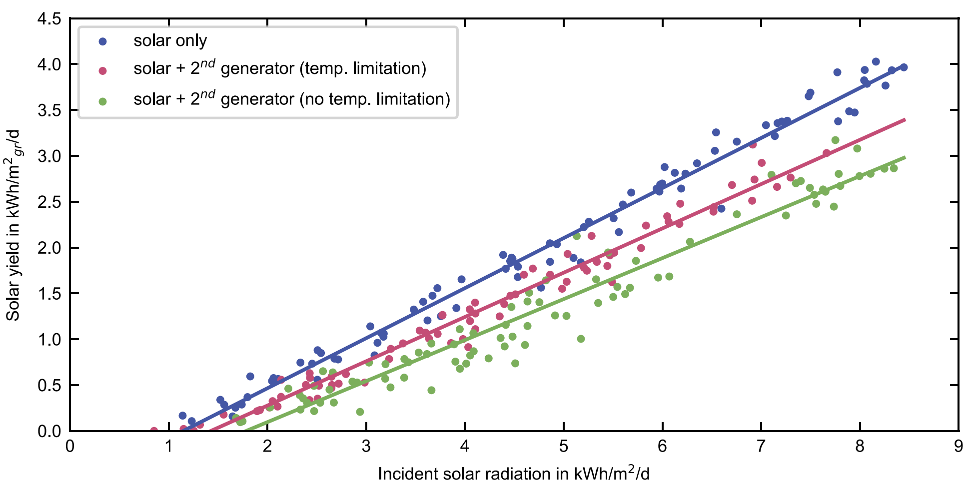

Fig. 11. Measured daily solar yield as a function of the measured daily solar radiation (in the collector plane) for different control strategies of the auxiliary heater of system D8. The straight lines represent the linear interpolation of the three datasets.

lar yield increased. The system also operated without the auxiliary unit (blue), showing a further increase in efficiency. The effect is significant, for a radiation of 6 kWh/m^2/d, adding the temperature limitation control improves the solar yield by 17 % while without auxiliary heater the gain amounts to 40 % compared to the initial situation. To further improve the gain with the auxiliary heater, not only the control parameters but also the construction parameters would have to be modified, which has not been implemented so far. In general, it is important that the connections of the auxiliary heaters are installed in such a way that they can only heat the upper third or even the upper quarter of the solar storage tank. Alternatively, a suitable control strategy should be implemented to ensure that there is always sufficient storage volume available for the solar thermal system, and that this volume can be properly discharged.

Finally, the importance of a good estimation of the load profile is highlighted. Several systems analysed show that the lack of sufficient information about the heat sink(s) during the planning phase can massively reduce the solar yield (F10). This is especially a problem if the heat demand is overestimated, leading to recurrent stagnation periods of the solar collector field during the summer and a reduced solar yield. Generally, special attention should be paid to the summer heat demand and the load profile of the heat sink during planning, which includes temperatures, heat demand, load peaks and related volume flow rates. Besides unwanted stagnation if these parameters are not sufficiently known, the selection of an unsuitable heat exchanger connecting the heat sink can, for example, lead to the process setpoint temperature not being reached, although there is sufficient heat available and the temperatures in the solar storage tank are high enough, or the flow temperature on the primary side of the heat sink heat exchanger must be

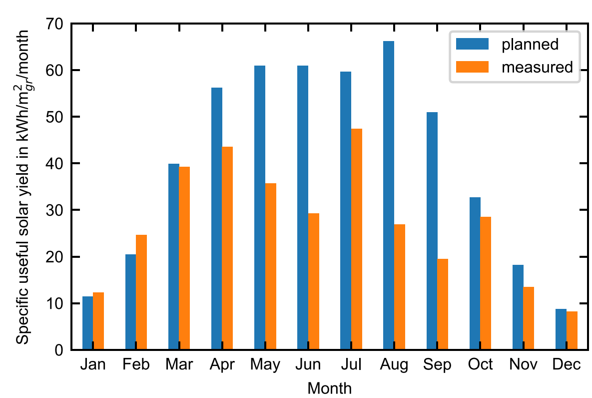

Fig. 12. Planned and measured monthly specific useful solar yield of system U5. The measured solar yield is averaged over two years, except for October and November for which only one month of data is available.

unnecessarily high. In the case of a load profile strongly characterised by load peaks, it is advisable to carry out a feasibility assessment for the addition of a batch storage tank continuously charged by the STS and emptied when heat is demanded by the process. An example of the effect of an overestimated heat demand is presented in Fig. 12. The predicted and measured (averaged over two years) specific useful solar yields are shown. There is good agreement between the planned and measured yields from October to March, while during the sunniest months from April to September the achieved yields are significantly lower than the predicted ones. A person in charge of the STS confirmed that the system had been deliberately oversized because increased activity, i.e. a higher heat demand, was expected in the future. At the time of the measurements shown in Fig. 12 the STS is still not being used at full capacity and regularly goes into stagnation during the summer period.

5. Discussion and conclusions

The deficiencies identified in most of the investigated systems show that the installation of measurement equipment for basic monitoring, in addition to the sensors required for system control, is crucial in SHIP plants to identify potential faults and ensure efficient operation. The monitoring of the following parameters is thus highly recommended:

- Thermal energy delivered from the collector field to the storage tank or, if the storage tank is used exclusively by the STS, thermal energy delivered from the storage tank to the process. Heat meters are an appropriate technology for this purpose. This measurement shows whether the projected solar yield is achieved in the real system.
- Outlet temperatures of the individual collector rows. These temperatures provide information about flow balancing between the collector rows and the proper operation of the pumps in the sub-collector fields. The measurements can reveal problems such as partial stagnation.
- Flow and return temperatures on the primary and secondary sides of the solar heat exchanger and, when applicable, on the primary and secondary sides of the heat exchanger connecting the heat sink, to evaluate the LMTDs. The sensors can also be used to detect degradation of the heat exchanger performances with time due to fouling.

In addition, the monitoring of the following parameters can be considered, even though the faults they reveal do not have the most significant impact on the performance in the systems investigated:

- Volume flow rate on the primary side of the solar collector loop to identify unbalanced capacity flows together with the volume flow rate of the heat meter from the secondary side.
- Temperature distribution over the storage height. Depending on the storage size, three to five sensors are usually sufficient. The aim is to evaluate the thermal stratification of the storage tank, e.g. to identify possible mixing during charging and discharging of the tank, which should be avoided for efficient operation of the STS.

Yet, monitoring the parameters mentioned above alone does not guarantee that optimisation potentials will be identified and the relevant measures implemented. The quality of the measurements is a first issue. For one of the studied plants, the measurement error was so obvious that correction factors were determined with additional on-site measurements. However, no systematic calibration of the sensors installed in the 13 plants was carried out, so that other measurement errors cannot be excluded. Generally, poor measurement quality makes it difficult to properly evaluate a system. In addition, when a problem is identified, it was shown during the BEsoPro project that suggestions for improvement are not necessarily implemented by the system operators or planners. Lack of interest and time as well as additional costs are the main reasons for not acting. Outside the project, it is also questionable who is responsible for the evaluation of measured data. Automated fault detection systems, even basic ones, would be helpful in this respect. Funding agencies are also advised to consider whether effective basic monitoring (internal or external) should be mandatory to ensure efficient use of funding.

In this non-representative study of SHIP plants, not properly functioning systems are unfortunately more common than properly functioning ones. Despite higher solar radiation levels in recent years compared to long-term averages, most systems did not deliver the expected solar yields. This is a serious issue as inefficient systems have the potential to tarnish the image of the reliable and market-ready SHIP technology and hinder the already slow market development of such systems.

The reasons for low solar yields are multiple and mostly plant specific. However, the ten most common faults and problems identified highlight the fact that most of them could be relatively easily avoided with better planning and installation of the systems. Particularly common are undersizing of the solar heat exchanger as well as undersizing of the pump(s) in the solar collector loop. Critical problems or major defects in the components or systems were not identified.

Even though SHIP plants are complex hydraulic systems, each plant and application having its own specificities, being aware of common issues should help planners and installers avoiding them. Complexity implies that a significant effort is required during the planning phase of a project, i.e. additional costs for the client. Access to practice-oriented tools for dimensioning components could help planners in this regard.

Declaration of Competing Interest

None.

Acknowledgements

The authors are thankful to the Federal Ministry for Economic Affairs and Climate Action (BMWK) for funding the research project BEsoPro within the framework of the 6th Energy Research Program (grant number: 03ETW003) and to the plant operators and planners as well as the Federal Office for Economic Affairs and Export Control (BAFA; SHIP funding administration) for the trustful cooperation and for sharing their data.

References

[1] W. Weiss, M. Spörk-Dür, Solar Heat Worldwide – Global Market Development and Trends in 2021 – Detailed Market Figures 2020, AEE INTEC, Gleisdorf, Austria (2022).
[2] Universität Kassel, Markt – Marktübersicht Deutschland, solar4industry.info (2021) (accessed April 8, 2022).
[3] VDISolarthermische Prozesswärme, VDI 3988, Beuth Verlag, Berlin, Germany, 2020.
[4] B. Epp, Controversial view of Germany's renewable industrial heat subsidy scheme, solarthermalworld.org (2022) https://solarthermalworld.org/news/controversial-view-of-germanys-renewable-industrial-heat-subsidy-scheme/. (accessed July 28, 2022).
[5] G. Faure, M. Vallée, C. Paulus, T.Q. Tran, Fault detection and diagnosis for large solar thermal systems: A review of fault types and applicable methods, Sol. Energy. 197 (2020) 472–484, doi:10.1016/j.solener.2020.01.027.
[6] C. Lauterbach, B. Schmitt, K. Vajen, System analysis of a low-temperature solar process heat system, Sol. Energy. 101 (2014) 117–130, doi:10.1016/j.solener.2013.12.014.
[7] C. Lauterbach, Potential, system analysis and preliminary design of low-temperature solar process heat systems, Kassel Univ. Press, Kassel, Germany, 2014.
[8] A.K. Sharma, C. Sharma, S.C. Mullick, T.C. Kandpal, Solar industrial process heating: A review, Renew. Sustain. Energy Rev. 78 (2017) 124–137, doi:10.1016/j.rser.2017.04.079.
[9] N. Tasmin, S.H. Farjana, M.R. Hossain, S. Golder, M.A.P. Mahmud, Integration of Solar Process Heat in Industries: A Review, Clean Technol 4 (2022) 97–131, doi:10.3390/cleantechnol4010008.
[10] C. Fink, S. Knabl, W. Wagner, R. Stelzer, B. Windholz, F. Helminger, 3. Zwischenbericht zum Projekt Wissenschaftliche Begleitforschung zum Förderprogramm "Solarthermie – Solare Großanlagen 2012", AEE - Institut für Nachhaltige Technologien, Gleisdorf, Austria, 2016.
[11] C. Fink, S. Knabl, W. Wagner, R. Stelzer, B. Windholz, F. Helminger, 2. Zwischenbericht zum Projekt Wissenschaftliche Begleitforschung zum Förderprogramm "Solarthermie – Solare Großanlagen 2013", AEE - Institut für Nachhaltige Technologien, Gleisdorf, Austria, 2016.
[12] C. Fink, S. Knabl, W. Becke, R. Pertschy, F. Helminger, M. Blöchle, T. Natiesta, 3. Zwischenbericht zum Projekt Wissenschaftliche Begleitforschung zum Förderprogramm "Solarthermie – Solare Großanlagen 2014", AEE - Institut für Nachhaltige Technologien, Gleisdorf, Austria, 2018.
[13] C. Fink, W. Becke, J. Binder, R. Pertschy, 2. Zwischenbericht zum Projekt Wissenschaftliche Begleitforschung zum Förderprogramm "Solarthermie – Solare Großanlagen 2017", AEE - Institut für Nachhaltige Technologien, Gleisdorf, Austria, 2020.
[14] W. Becke, C. Fink, M. Hamilton-Jones, R. Pertschy, C. Rohringer, Monitoring-Ergebnisse von großen Solarthermie-Anlagen für Trocknungsanwendungen, in: Proc. Online Symp. Solarthermie Innov. Wärmesysteme, online, 2021.
[15] J. Möllenkamp, Enhanced Methods for Performance Evaluation and Fault Detection of Concentrating Solar Process Heat Plants Based on Experimental Analysis of Two Parabolic Trough Plants in Switzerland, PhD Thesis, Unpublished results, University of Kassel, n.d.

[16] C.F. Kutscher, R.L. Davenport, Preliminary Operational Results of the Low-Temperature Solar Industrial Process Heat Field Tests, Solar Energy Research Institute (SERI), Golden, Colorado, USA, 1980.

[17] M. Karagiorgas, A. Botzios, T. Tsoutos, Industrial solar thermal applications in Greece – Economic evaluation, quality requirements and case studies, Renew. Sustain. Energy Rev. 5 (2001) 157–173.

[18] L. Wimmer, D. Ritter, Y. Louvet, R. Heinzen, D. Grebe, K. Vajen, U. Jordan, Monitoring of renewable process heat plants within the gas sector, in: Proc. ISES Sol. World Congr. 2019, Santiago, Chile, 2019, doi:10.18086/swc.2019.12.14.

[19] A. Anthrakidis, C. Faber, J. Kroker, M. Lanz, K. Backes, M. Adam, M. Dreher, S. Schramm, Solare-Prozesswärme-Standards (Sol-Pro-St), in: Proc. 20 Symp. Thermische Solarenergie, Bad Staffelstein, Germany, 2010.

[20] A. Vittoriosi, R. Fedrizzi, R. Brock, F. Orioli, V. Orioli, D. Pietruschka, Monitoring of a MW Class Solar Field Set up in a Brick Manufacturing Process, Energy Procedia 48 (2014) 1217–1225, doi:10.1016/j.egypro.2014.02.138.

[21] Y. Louvet, D. Ritter, F. Pag, R. Heinzen, D. Grebe, K. Vajen, Innovative erneuerbare Wärmeversorgungskonzepte für die Dekarbonisierung des Gastransportsektors, in: Proc. 31 Symp. Solarthermie Innov. Wärmesysteme, Bad Staffelstein, Germany, 2021.

[22] S. Schramm, M. Adam, Storage in Solar Process Heat Applications, Energy Procedia 48 (2014) 1202–1209, doi:10.1016/j.egypro.2014.02.136.

[23] I.B. Hassine, M.C. Sehgelmeble, R. Söll, D. Pietruschka, Control Optimization through Simulations of Large Scale Solar Plants for Industrial Heat Applications, Energy Procedia 70 (2015) 595–604, doi:10.1016/j.egypro.2015.02.166.

[24] M. Wutzler, U. Schirmer, B. Platzer, Solar process heat application at the Hofmuehl brewery at Eichstätt /Germany, in: Proc. ISES Sol. World Congr. 2011, Kassel, Germany, 2011, doi:10.18086/swc.2011.23.19.

[25] P. Frey, S. Fischer, H. Drück, K. Jakob, Monitoring Results of a Solar Process Heat System Installed at a Textile Company in Southern Germany, Energy Procedia 70 (2015) 615–620, doi:10.1016/j.egypro.2015.02.168.

[26] S. Ushak, M. Grágeda, D. Pulido, E. Oró, L.F. Cabeza, Application of Solar Heating on the Electrolyte Conditioning for Electrowinning Process: Thermosolar Plant Performance, Energy Procedia 57 (2014) 2930–2936, doi:10.1016/j.egypro.2014.10.328.

[27] D. Pietruschka, I.B. Hassine, M. Cotrado, R. Fedrizzi, M. Cozzini, Large Scale Solar Process Heat Systems -planning, Realization and System Operation, Energy Procedia 91 (2016) 638–649, doi:10.1016/j.egypro.2016.06.223.

[28] J. Nagaraju, S.S. Garud, K. Ashok Kumar, M. Ramakrishna Rao, 1 MWth industrial solar hot water system and its performance, Sol. Energy. 66 (1999) 491–497.

[29] M. Cozzini, M. Pipiciello, R. Fedrizzi, Monitoring of a Concentrating Solar Thermal Field: Energy Measurements and Uncertainty Analysis, Institute for Renewable Energy EURAC Research, Bolzano, Italy, 2015.

[30] G. Faure, Etude de défauts critiques des installations solaires thermiques de grande dimension : définition, modélisation et diagnostic, Université Grenoble Alpes, 2018 PhD Thesis.

[31] VDIFunctional checking and yield rating of solar thermal systems, VDI 2169, Beuth Verlag, Berlin, Germany, 2012.

[32] Deutsche Gesellschaft für Sonnenenergie, Planning and installing solar thermal systems: a guide for installers, architects and engineers, Fully rev. & updated, 2nd ed., Earthscan, London, 2010.

[33] F. Brandstetter, Qualitätssicherung solarthermischer Großanlagen – Qualitätssteigerung und Qualitätssicherung großer thermischer Solaranlagen in gebäudeübergreifenden Mikronetzen und im großvolumigen Geschoßwohnbau, Bundesministeriums für Verkehr, Innovation und Technologie, Wien, Austria, 2007.

[34] P. Olivier, C. Felder, J. Grandjean, Etude d'optimisation des installations d'eau chaude sanitaire solaire en logement social – Rapport d'analyse transversale de l'expertise de 15 installations de production d'ECS solaire, L'union sociale pour l'habitat, Paris, France, 2014.

[35] R. Croy, M. Mies, U. Rehrmann, H.P. Wirth, Solarthermie-2000, Teilprogramm 2 und Solarthermie2000plus – Wissenschaftlich-technische Programmbegleitung und Messprogramm (Phase 4) – Teil 1: Stand der Technik und Langzeitverhalten von Solaranlagen, ZfS – Rationelle Energietechnik GmbH, Hilden, Germany, 2011.

[36] E. Scheck, E. Bollin, K. Huber, D. Jödicke, Funktionskontrolle solarthermischer Großanlagen auf Basis von Langzeitmonitoring durch die Hochschule Offenburg, in: Proc. 20 Symp. Thermische Solarenergie, Bad Staffelstein, Germany, 2010.

[37] C. Fink, R. Riva, M. Pertl, W. Wagner, OPTISOL – Messtechnisch begleitete Demonstrationsprojekte für optimierte und standardisierte Solarsysteme im Mehrfamilienwohnbau, AEE - Institut für Nachhaltige Technologien, Gleisdorf, Austria, 2006.

[38] A. Thür, G. Kuhness, J. Breidler, CombiSol – Solar-Kombianlagen für Einfamilienhäuser – Stand der Technik und Optimierungspotenziale, AEE - Institut für Nachhaltige Technologien, Gleisdorf, Austria, 2011.

[39] J. Breidler, A. Thür, Umfangreiche Evaluierung und Monitoring von solaren Kombianlagen im Einfamilienhausbereich, in: Proc. 20 Symp. Thermische Solarenergie, Bad Staffelstein, Germany, 2010.

[40] B. Sitzmann, Qualitätsprüfung thermische Solaranlagen 2013 – Schlussbericht, Energie Zukunft Schweiz, Basel, Switzerland (2013).

[41] C. Fink, J. Breidler, D. Ederer, R. Kapferer, H. Burtscher, A. Reiter, Funktionalitäts- und Qualitätsanalyse bei 120 Solarsystemen im Geschoßwohnbau und in gewerblichen Anwendungen, in: Proc. 20 Symp. Thermische Solarenergie, Bad Staffelstein, Germany, 2010.

[42] T. Darjay, C. Dorji, T. Lhendup, M. Elborg, Fault Analysis of Solar Thermal Systems in Bhutan, Sukatha Procedia (2021) 60–71, doi:10.32438/SA.120.3004.

[43] H. ur Rehman, J. Hirvonen, K. Sirén, Influence of technical failures on the performance of an optimized community-size solar heating system in Nordic conditions, J. Clean. Prod. 175 (2018) 624–640, doi:10.1016/j.jclepro.2017.12.088.

[44] G. Faure, M. Vallée, C. Paulus, T.Q. Tran, Impact of faults on the efficiency curve of flat plate solar collectors: a numerical analysis, J. Clean. Prod. 231 (2019) 794–804, doi:10.1016/j.jclepro.2019.05.122.

[45] DWD, Data Discovery, CDC – Climate Data Center (2022) https://cdc.dwd.de/portal/202204011005/searchview. (accessed April 8, 2022).

[46] DINWärmezähler – Teil 1: Allgemeine Anforderungen; Deutsche Fassung EN 1434-1:2015, DIN EN 1434-1:2016-02, Beuth Verlag, Berlin, Germany, 2016.

[47] DINLüftung von Gebäuden – Prüf- und Messverfahren für die Übergabe raumlufttechnischer Anlagen; Deutsche Fassung EN 12599:2012, DIN EN 12599:2013-01, Beuth Verlag, Berlin, Germany, 2013.

[48] DWD, Data set description – Gridded annual sum of incoming shortwave radiation (global radiation) on the horizontal plain for Germany based on ground and satellite measurements – Version V003, DWD, Offenbach (2018).

[49] D. Ritter, L. Paape, B. Schmitt, K. Vajen, Recommendations for the Reduction of Failures During the Planning and Installation Phases of Solar Thermal Process Heat Systems, in: Proc. EuroSun 2016 Conf., Palma de Mallorca, Spain, 2016, doi:10.18086/eurosun.2016.02.06.

[50] M. Wild, S. Wacker, S. Yang, A. Sanchez-Lorenzo, Evidence for Clear-Sky Dimming and Brightening in Central Europe, Geophys. Res. Lett. (2021) 48, doi:10.1029/2020GL092216.

[51] F.A. Peuser, R. Croy, M. Mies, U. Rehrmann, H.P. Wirth, Solarthermie-2000, Teilprogramm 2 und Solarthermie2000plus Wissenschaftlich-technische Programmbegleitung und Messprogramm (Phase 3), ZfS Rationelle Energietechnik GmbH, Hilden, Germany, 2009.

[52] F.A. Peuser, K.-H. Remmers, M. Schnauss, Langzeiterfahrung Solarthermie: Wegweiser für das erfolgreiche Planen und Bauen von Solaranlagen, Solarpraxis, Berlin (2001).