SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

SolarPACES
Solar Power & Chemical Energy Systems

Integration Concepts and Design Guidelines

IEA SHC TASK 64 | IEA SolarPACES Task 4 | Solar Process Heat

Technology Collaboration Programme
by iea

Integration Concepts and Design Guidelines

This is a report from SHC Task 64 / SolarPACES Task IV: Solar Process Heat and work performed in Subtask A: Integrated Energy Systems

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Solar Heating and Cooling Technology Collaboration Programme (IEA SHC)

The Solar Heating and Cooling Technology Collaboration Programme was founded in 1977 as one of the first multilateral technology initiatives ("Implementing Agreements") of the International Energy Agency.

Our mission is *To bring the latest solar heating and cooling research and information to the forefront of the global energy transition.*

IEA SHC members carry out cooperative research, development, demonstrations, and exchanges of information through Tasks (projects) on solar heating and cooling components and systems and their application to advance the deployment and research and development activities in the field of solar heating and cooling.

Our focus areas, with the associated Tasks in parenthesis, include:

- Solar Space Heating and Water Heating (Tasks 14, 19, 26, 44, 54, 69)
- Solar Cooling (Tasks 25, 38, 48, 53, 65)
- Solar Heat for Industrial and Agricultural Processes (Tasks 29, 33, 49, 62, 64)
- Solar District Heating (Tasks 7, 45, 55, 68)
- Solar Buildings/Architecture/Urban Planning (Tasks 8, 11, 12, 13, 20, 22, 23, 28, 37, 40, 41, 47, 51, 52, 56, 59, 63, 66)
- Solar Thermal & PV (Tasks 16, 35, 60)
- Daylighting/Lighting (Tasks 21, 31, 50, 61, 70)
- Materials/Components for Solar Heating and Cooling (Tasks 2, 3, 6, 10, 18, 27, 39)
- Standards, Certification, Test Methods and LCA/LCoH (Tasks 14, 24, 34, 43, 57, 71)
- Resource Assessment (Tasks 1, 4, 5, 9, 17, 36, 46)
- Storage of Solar Heat (Tasks 7, 32, 42, 58, 67)

In addition to our Task work, other activities of the IEA SHC include our:

- ➢ SHC Solar Academy
- ➢ *Solar Heat Worldwide*, annual statistics report
- ➢ SHC International Conference

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Solar Power and Chemical Energy Systems Technology Collaboration Programme (IEA SolarPACES)

The SolarPACES Technology Collaboration Programme was founded in 1977 as one of the first multilateral technology initiatives (“Implementing Agreements”) of the International Energy Agency.

Our mission is to facilitate technology development, market deployment and energy partnerships for sustainable, reliable, efficient and cost-competitive concentrating solar power technologies by providing leadership as the international network of independent experts.

To realize this mission, SolarPACES coordinates and advances concentrating solar technology research, by focusing on the next generation of technologies, by providing information and recommendations to policy makers and by organizing international conferences, workshops, reports and task meetings.

Our focus areas are organized in six tasks:

- Task I: Solar Thermal Electric Systems
- Task II: Solar Chemistry Research
- Task III: Solar Technology and Advanced Applications
- Task IV: Solar Heat Integration in Industrial Processes
- Task V: Solar Resource for High Penetration and Large Scale Applications
- Task VI: Solar Energy and Water Processes and Applications

In addition to our Task work, other activities of the IEA SolarPACES include:

- ➢ SolarPACES International Conference.
- ➢ Review of CSP market and cost data with the International Renewable Energy Agency (IRENA).
- ➢ Joint project on solar resource for high penetration and large scale applications in collaboration with the TCP on Photovoltaic Power Systems (PVPS TCP).
- ➢ Project in solar process heat in collaboration with the TCP on Solar Heating and Cooling (SHC TCP).

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Contents

1 Introduction

The defossilization of the industrial heat supply is crucial for achieving the Paris climate targets. For the defossilization of heat with supply temperatures of at least 150 °C, solar thermal heat for industrial processes (SHIP) and heat pumps (HP) are technically mature technologies that allow a complete substitution of fossil-fueled systems already today [1]. However, the individual potential of these technologies is often limited by restrictions regarding the availability of renewable energy sources, e.g., solar radiation, environmental or excess heat, or by technical limitations, e.g., the available space for solar thermal collectors. The combination of both technologies could, therefore, be a solution to maximize the degree of defossilization and overall efficiency.

The combination of solar thermal systems and HPs is a popular topic for residential applications and has been investigated, e.g., in the IEA SHC Task 44 on “Solar and Heat Pump Systems”. For industrial applications, on the other hand, there is little research and hardly any practical experience. In twelve case studies from five different industries, the Austrian research project "ENPRO" exemplarily assessed the potential of o heating systems with HPs and SHIP individually and in combination. The results show an overall high potential of GHG savings of about 19,000 t CO2 /a for the analyzed twelve case studies combined [2]. However, the ENPRO project only gives qualitative advice on the system design. A systematic investigation of the potential of combined SHIP and HP systems, which would allow conclusions on when these systems are particularly suitable and how they should be designed depending on the location and application, is missing so far. To fill this gap, Subtask A aims to answer the following questions:

- How can SHIP, HP, thermal storage and backup heaters be hydraulically connected?
- How should SHIP and HP be dimensioned when coupled?
- How to consider different locations and applications in system design?
- Which renewable fractions are (economically) feasible depending on location and application?

The possible range of applications of combined SHIP and HP plants is broad. To find generally valid answers to the questions above, particular importance was paid to the definition of the applications to be studied. The methodology for defining the reference applications in Task 64/IV was published earlier [3].

This work is a summary of the outcomes of Subtask A. A full overview of the outcomes can be found in Pag et al. (2022) [4] and Jesper et al. (2023) [1].

2 Description of the Analyzed Integration Concepts

To combine both heat generators, one parallel and three serial hydraulic concepts with backup boiler (SGB) were developed in the ENPRO project. The parallel system (Figure 1, P) and two of the serial systems (Figure 1, S1 and S2) use an external heat source for the HP, e.g., environmental heat or excess heat. These hydraulic concepts are potentially capable of completely replacing fossil heat generators in many cases, considering the enormous potential of unused industrial heat that several recent studies point to [5–7].

In the parallel hydraulic concept, all heat generators need to provide the required secondary flow temperature all the time. In the serial hydraulic concepts, the temperature difference between the flow and return temperatures is divided among the three heat generators. The first heat generator in each serial hydraulic concept supplies the lowest flow temperature. The efficiency of the renewable heat depends on their secondary flow temperature, which leads to a more efficient SHIP plant (S1) or a higher Seasonal Coefficient of Performance (SCOP) of the HP (S2). However, if solar heat is available, it always takes priority, and the output of the other heat generators is consequently reduced to minimize electrical energy consumption and greenhouse gas emissions (GHGE).

The third serial hydraulic concept (S3), developed in the ENPRO project, involves using the SHIP plant as the heat source for the HP and is not reviewed in this work for the following reason: The HP primarily enhances the efficiency of the SHIP plant by lowering the required collector outlet temperature. Without a seasonal storage, the operation of the HP in this concept is limited to times of solar irradiation. Therefore, if other heat sources, such as excess heat, are available, which is the case for many industrial companies, these alternative heat sources should be used to reach higher renewable fractions.

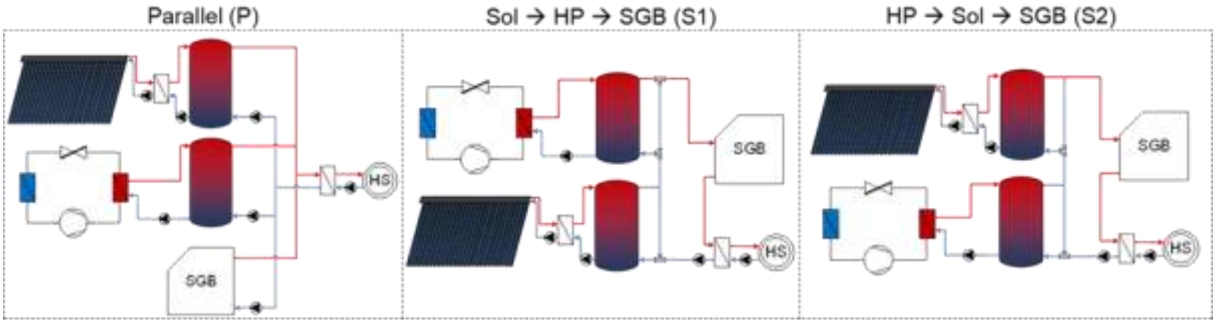

Figure 1: Parallel and serial hydraulic concepts (adapted from [2]).

3 Recommendations for System Design

3.1 Selection of integration concept

Figure 2 shows the specific yield of the collector circuit (q_{col}) as a function of the flow temperature of the SHIP plant and the location. These results were calculated assuming that the supplied heat is used by the heat sink completely without losses (except the collector losses) at any time. The collector was modeled based on the collector efficiency curves of a static CPC collector (st) and a two-axes tracking concentrating collector (csh). The flow temperatures of 90 °C and 160 °C represent temperatures in regular operation required by the defined reference applications. When the irradiation is not sufficient to meet the total heat demand of the heat sink in the S1 or S2 hydraulic concept, the SHIP plant is operated in a preheating mode to reduce the collector output temperature and increase the SHIP plant's efficiency. The temperatures of 70 °C and 140 °C represent the minimum temperatures that could be reached during the preheating operation mode in the case of a commonly used spread between flow and return temperature of 20 K.

Figure 2 is based on the assumption that the SHIP plant is operated the whole year with the respective temperatures depicted in Figure 2. In practice, the the flow temperature will be higher than the minimum temperatures of 70 °C and 140 °C most of the time. Therfore, the differences between both temperature levels will be lower in practice than illustrated in Figure 2.

Due to the almost horizontal efficiency curve, the higher temperature level leads to a reduction of the collector yield of a maximum of 3 % for csh only and will, therefore, be negligible in practice. For st, the differences are ranging between 7 % and 10 %. Since the actual differences in practice will be much smaller, it can be concluded that the serial hydraulic concepts hardly add any value to the SHIP plant in practice. This is especially the case if one takes into account that a sophisticated control of the respective volume flows is required in order to achieve any advantage at all with the serial concepts. However, if the difference between supply and return temperature is more than 20 K, the benefit of a serial concept might be higher and should be investigated further.

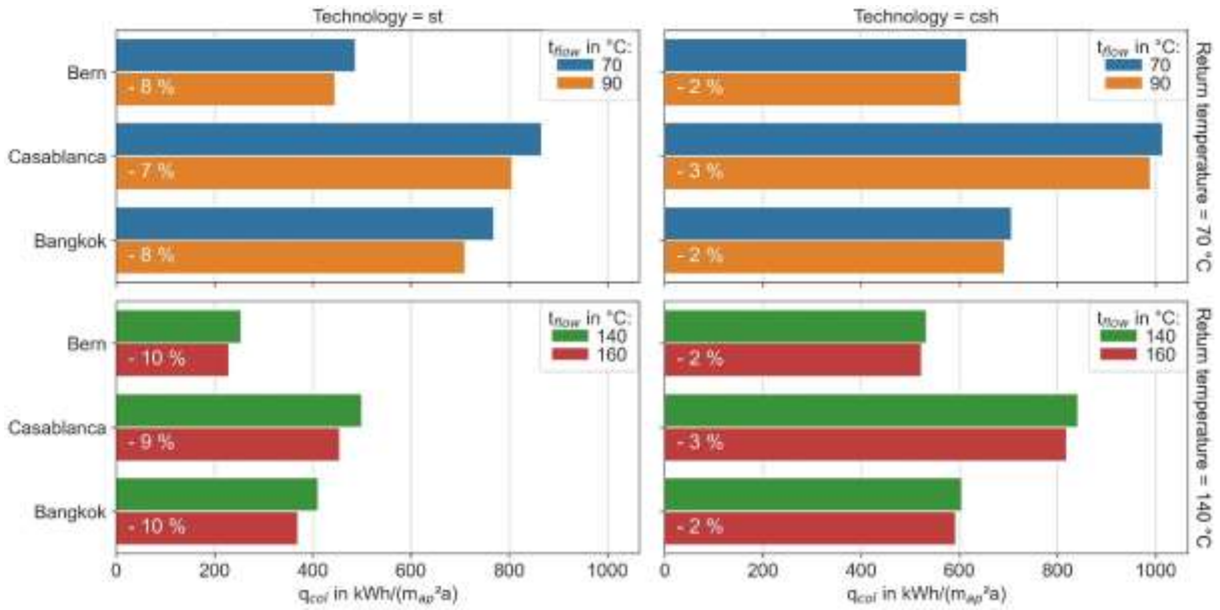

Figure 2: q_{col} as a function of the location and t_{flow}.

Figure 3 shows the distribution of the SCOP depending on the different parameters defining the reference applications and the technical design of the combined SHIP and HP system in the form of boxplots. The system design can have a substantial impact on the SCOP. This is made clear by the boxplots for the hydraulic concept and the HP's capacity ratio. While the hydraulic concept does not affect about three-quarters of the reference applications examined, the SCOP of the serial concepts is increased for the other quarter. The capacity ratio is the quotient of the heat output of the HP and the maximum heat demand during the year. The results show that a HP dimensioning with a capacity ratio of at least 0.4 to 0.5 is sufficient to cover most of the heat demand (> 90 %) in any case. The serial hydraulic concepts only show relevant advantages of the SCOP if the HP is operated in preheating mode for a relevant part of the year, which is only the case for capacity ratios below 0.4. Since the temperatures of the heat source and the heat sink are assumed to be constant throughout the year, the location, the annual load profile type (wd cluster) and the daily load profile type have almost no effect on the SCOP. In contrast, the heat source temperature has a massive impact on the SCOP.

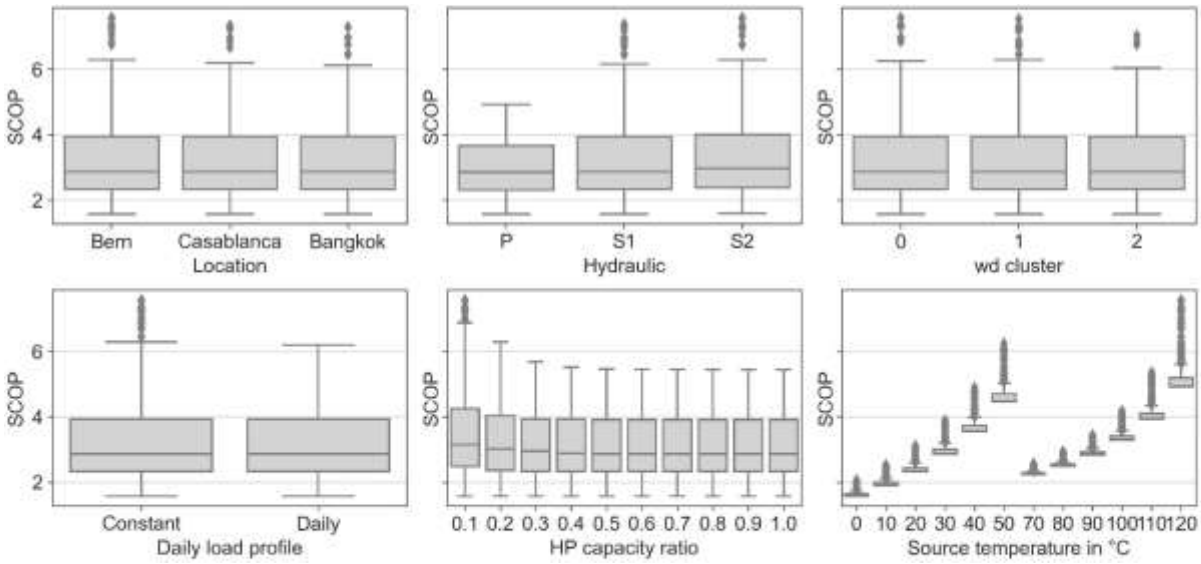

Figure 3: Distribution of the SCOP of the HP depending on different parameters determined by the application.

3.2 Storage integration and management

Large heat storages are the core element of future flexible heating systems with high shares of renewable heat. Typically, the storage of solar heating plants is relatively big compared to the storage of other technologies as these are designed more often with respect to a daily than an hourly scale. Furthermore, the full scale of the solar storage is specifically needed in summer, and many hours per year, the potential of the storage cannot be fully exploited. Consequently, other technologies can benefit from the big solar storage and use it in parallel with the solar heating plant. By using solar storage, other technologies can operate much more smoothly, and the start cycles can be massively reduced. Depending on the combination of load profile and system design, the annual start cycles can be reduced by more than two-thirds. This brings benefits to the overall system costs as during the starting phase, other technologies work less efficiently, and a high number of starting cycles reduces lifetime and increases maintenance costs.

Figure 4 shows the results of a simulation study from a solar heating plant that is operated in parallel with a CHP in one common storage [8]. Obviously, the CHP can charge the upper half of the heat storage while the solar yield is only affected minorly. In contrast, if the CHP is allowed to charge more than half of the solar storage, the solar yield will be massively reduced. As solar storage tanks are typically much larger than those of other technologies, as discussed above, the use of solar storage tanks can be expected to have positive effects on other heat generators without significant negative effects on the operation of the solar heating system.

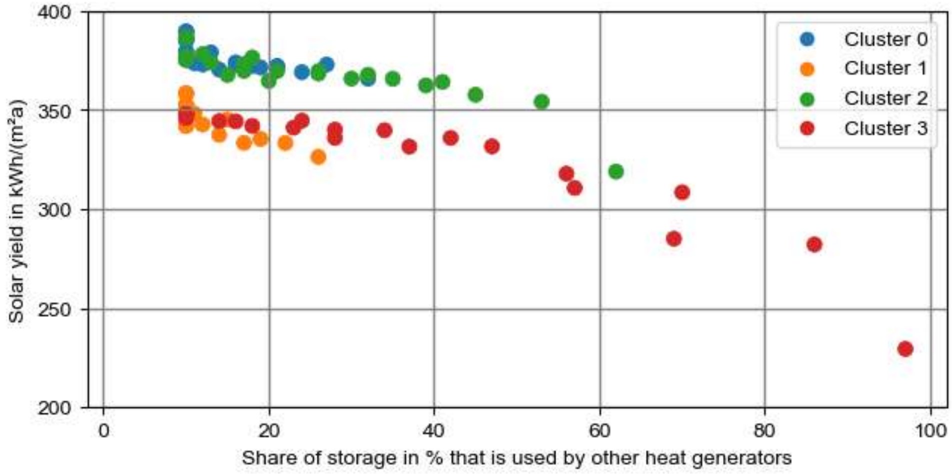

Figure 4: Specific solar yield as a function of the share of the solar storage that is charged by the other heat generators for different heat load clusters.

4 Achievable Solar Fractions

4.1 Limitations of solar fraction by the availability roof area and the seasonality of the heat load profile

Several potential studies within Task 49/IV mentioned the availability of roof areas as a limiting factor for the implementation of solar collectors in Industry [9]. Furthermore, the seasonality of the heat load demand only played a minor role in the estimation of the potential solar fraction in these studies so far. As shown in DA.1 [3], ambient temperature dependent heat demand can take a significant share of the overall heat demand within an industrial company. A study within Task 64/IV with 489 industrial companies showed that 60 % of the analyzed companies have enough roof area available to design the solar heating plant, according to VDI 3988 [4]. As shown by Figure 5 (a), the potential solar fraction is in the range of around 35 % (Cluster 0, no ambient temperature dependency) to less than 5 % (Cluster 3, strong ambient temperature dependency). In contrast, the potential solar fraction is significantly reduced for the companies where there is not enough roof area available (Figure 5 (b), left to the dashed line). Especially the companies with high summer heat demand and subsequent large collector areas are affected negatively.

These results underline, that the design according to the VDI 3988 is a minimum design strategy with respect to the solar fraction to be reached but a good first estimate to evaluate the area availability. Taking into account the ambitious goals for renewable heat in Industry, the design of solar process heat plant should also target on the ambient dependent heat demand, e.g. heating of production halls.

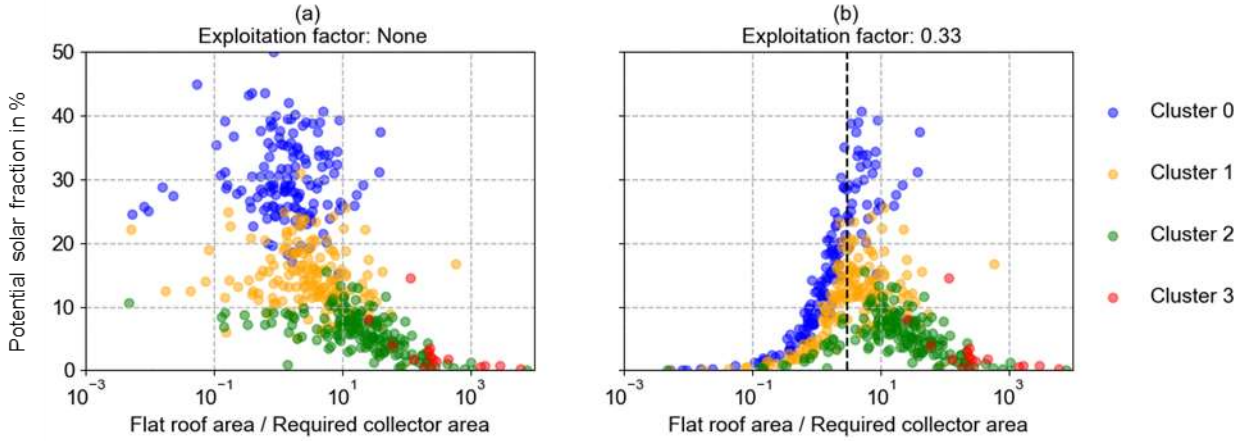

Figure 5: Solar fraction % for every company as a function of the relation of the roof area and the required collector area according to VDI 3988; every marker represents one company; Cluster 0: no ambient temperature dependency, Cluster 3: strong ambient temperature dependency of the load profile according to (XY -ref Jesper), (a) availability of roof areas is not taken into account, (b) realistic usage of the available roof area with solar collectors

4.2 Limitations by load profile and location

Figure 6 shows the solar fraction (f_{sol}) for a SHIP plant designed according to the VDI 3988 guideline [10] as a function of the location and the annual load profile type (wd cluster). The annual load profiles are created based on clustering and regression analysis of 797 natural gas load profiles of industrial and other large natural gas consumers [11]. The wd cluster 0 represents consumers dominated by process heat demand with a more or less constant heat demand on every weekday. From wd cluster 1 to 2, the seasonality of the heat demand is increasing. Wd cluster 2 represents consumers that are dominated by space heating demand and are therefore only considered in Bern.

Since there is no comparable design standard for concentrating systems to the VDI 3988 guideline, which is only applicable for st, the dimensioning of the csh plant was iteratively adapted to meet the solar yield of the st system. This explains the same f_{sol} for st and csh systems in Figure 6.

Casablanca is the location with the highest and most constant irradiation, which pays off in the highest fsol, at least 50 %. Especially the less constant irradiation in Bangkok results in a slightly lower f_{sol}. Bern is the place with the most pronounced seasonal weather differences. This results in about a halving of the f_{sol} compared to

Casablanca and Bangkok. Due to the more constant heat demand of the non-seasonal annual load profile (wd cluster 0), it reaches clearly higher f_{sol} than both seasonal annual load profiles (wd clusters 1 and 2).

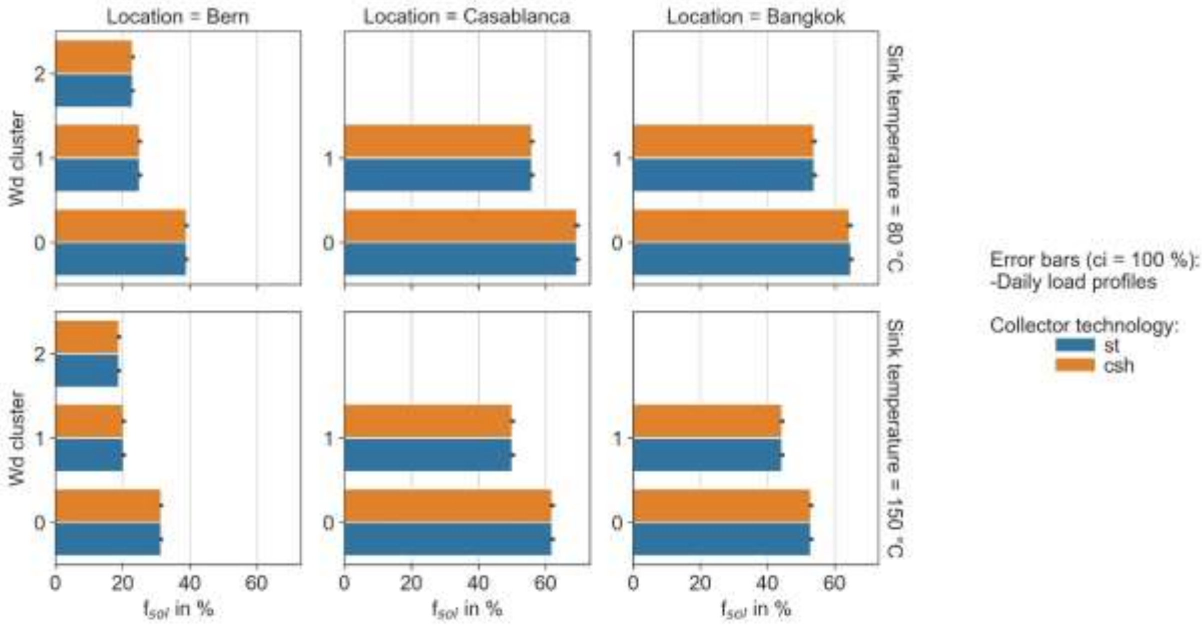

Figure 6: f_{sol} as a function of the location and the load profile type (wd cluster).

Figure 7 shows a comparison of different SHIP dimensionings compared to a dimensioning according to the VDI 3988. To reach higher solar fractions, the dimensioning of the SHIP plant can be increased without a drastic loss of the specific collector yield. In the case of Bern, a 50 % increase of the collector area, the maximum decrease of the specific yield is 10 %. Even if the collector area is tripled, the specific yield only drops by about 20 % for the two seasonal annual load profiles (wd clusters 1 and 2). Consequently, the solar fraction increased close to linearly without reaching saturation. Only the constant annual load profile (wd cluster 0) shows significantly greater losses in the specific collector yield since a higher coverage ratio is achieved overall. Thus, the course of the solar fraction shows a saturation if the collector area is oversized by more than 50 %. If over dimensioning is being considered in practice, stagnation-proof collectors and system design should be taken into account. Considering that especially companies with strong seasonal heat load profiles can only reach a minor solar fraction of the overall heat demand with the design according to the VDI 3988 but show to have more roof area available (compare Figure 5), larger solar thermal systems designs should be taken into account.

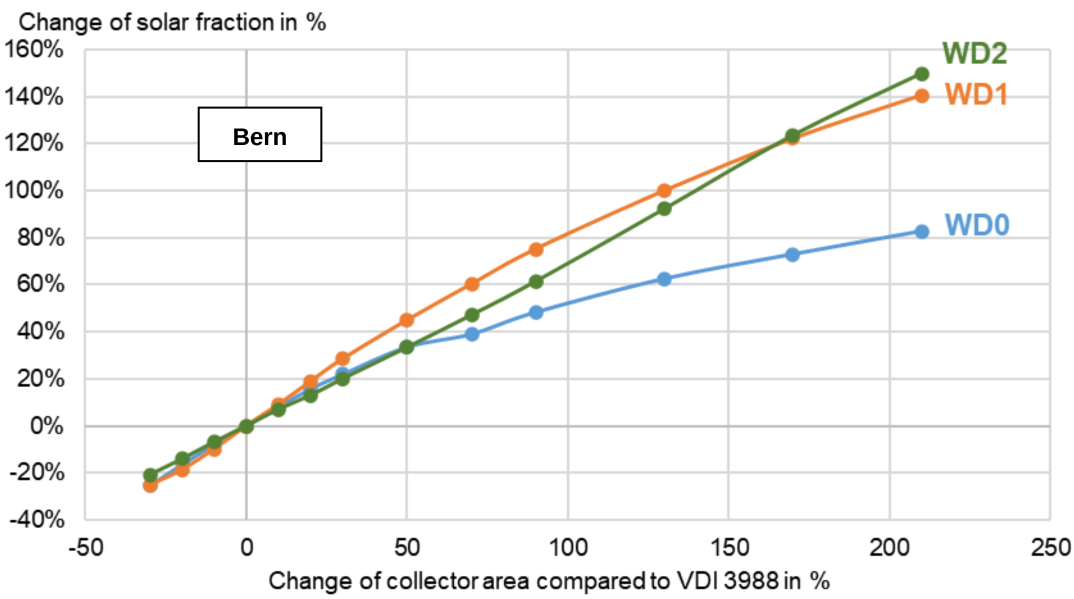

Figure 7: Change of solar fraction compared to the reference design as a function of the collector field size (st collector; Bern; 0 % equals a dimensioning according to the VDI 3988 guideline [10])

Corresponding to results of wd cluster 0 in Bern, the results for the locations Casablanca (Figure 8) and Bangkok (Figure 9) also show a strong saturation of the increase of the solar fractions. On the one hand, this is due to the less seasonal heat load profiles in these locations, on the other this is related to the much higher solar fractions which can be achieved with the reference design at these locations.

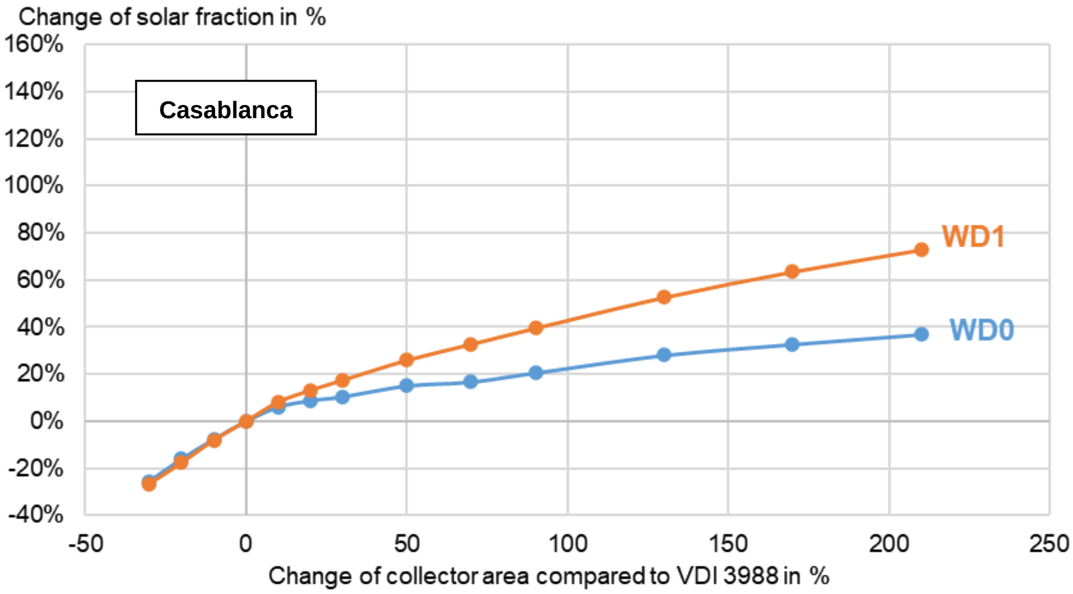

Figure 8: Change of solar fraction compared to the reference design as a function of the collector field size (st collector; Casablanca; 0 % equals a dimensioning according to the VDI 3988 guideline [10])

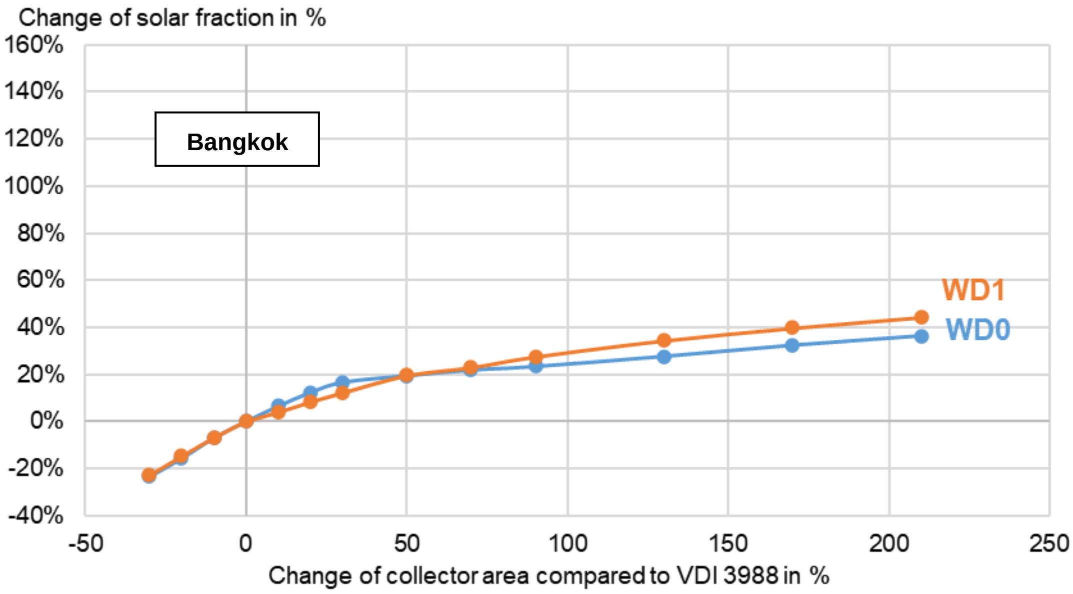

Figure 9: Change of solar fraction compared to the reference design as a function of the collector field size (st collector; Bangkok; 0 % equals a dimensioning according to the VDI 3988 guideline [10])

5 Design Heat Generators

To achieve a cost-efficient design of the SHIP plant, the design strategy according to the German VDI guideline 3988 on solar process heat [10] has proven successful for non-concentrating systems. By designing the system to supply the summer working day heat demand, heat surpluses are prevented to a large extent. However, due to a lower heat demand at weekends, the unused heat production of the non-concentrating SHIP plants still sums up to a maximum of 12 % for the investigated applications (Figure 10). As shown in Figure 7, the specific solar yield and, consequently, the economic performance does not collapse for significantly larger systems. Therefore, the design approach, according to VDI 3988, mainly represents a lower limit but can be exceeded in most cases without major economic losses if higher solar fractions are desired.

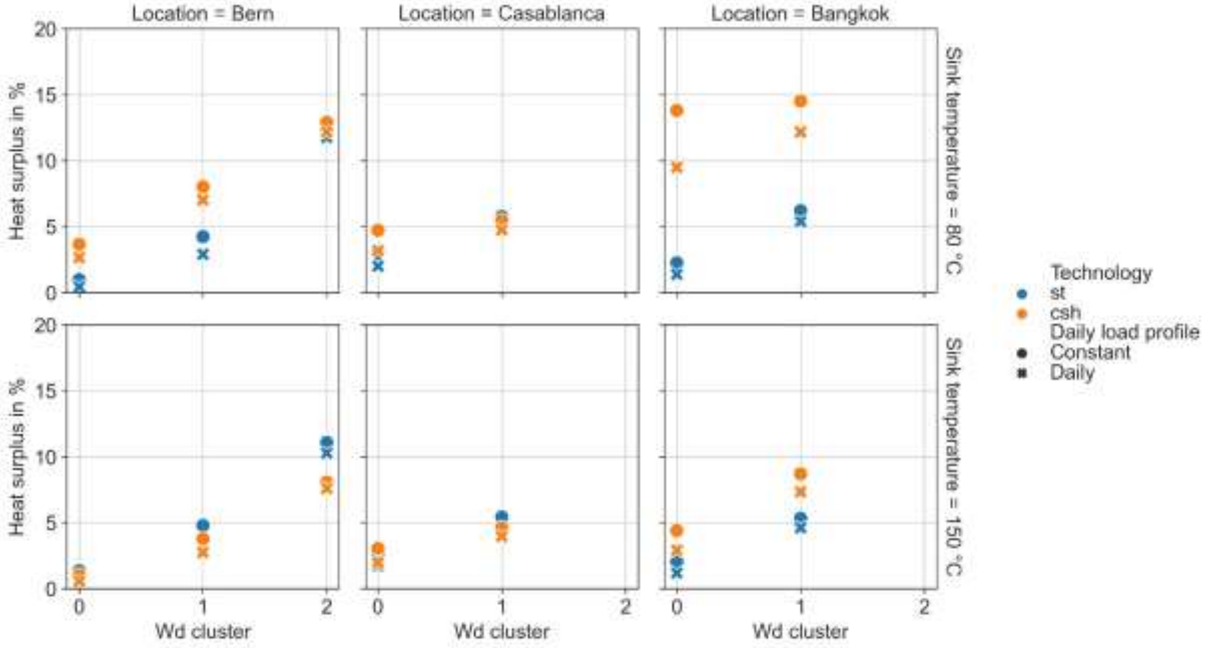

Figure 10: Heat surpluses of the SHIP plant as a function of the location, the annual load profile type (wd cluster), the collector technology and the daily load profile type.

First, the csh system was designed analogous to the st system to just achieve 100 % coverage of the heat demand on working days with a direct normal irradiation of at least 7 kWh/m². Due to the high efficiency of csh systems and high peaks of daily direct irradiation on summer days, the resulting csh systems are relatively small compared to the st system. Since the hemispherical irradiation used by non-concentrating systems is distributed more evenly over the year compared to the direct irradiation used by concentrating systems (**Figure 11**), the achieved solar fractions of the csh system are significantly smaller compared to the st system when both systems are designed according to the described approach.

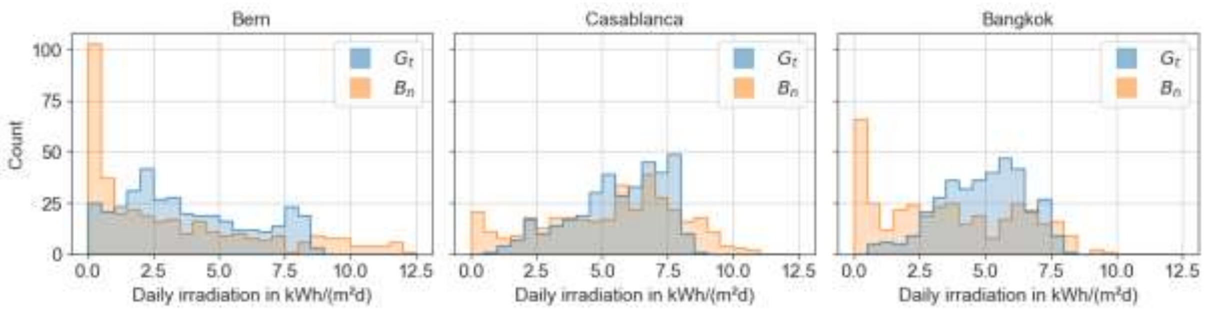

Figure 11: Histogram of daily sums of hemispherical (Gt) and normal direct irradiation (Bn).

Due to the possibility of defocusing and oversizing concentrating SHIP plants has no significant negative impact on technical and economic performance. In practice, concentrating systems should, therefore, be designed with regard to a desired solar fraction and the available collector area. To enable a comparison of the two collector technologies, the collector area of the concentrating system was iteratively adjusted in the simulation study until it reached the same yield as the non-concentrating system. This explains the partly significant increased heat surpluses of the csh system compared to the st system shown in Figure 10. Figure 12 shows a boxplot of the adaption factors of the csh collector area required to reach the same solar yield as the non-concentrating system. For the lower heat sink temperature level of 80 °C, the csh system collector area is increased by about 10 % to 40 %. For the higher temperature level, st collectors are significantly less efficient compared to csh collectors, which explains the relatively low to negative adjustment of the collector area. This is especially true for Bern, where the ambient temperature and irradiation are usually significantly below the other two locations.

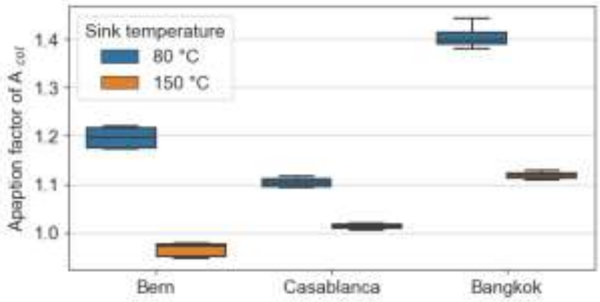

Figure 12: Iterative adaptation factor of the csh collector area to meet the solar yield of the st system designed according to the VDI 3988 guideline.

In the performed simulation study, solar heat is always prioritized. If no sufficient solar heat is available, the HP is used to supply the remaining heat demand. If the capacity of the HP is not sufficient and the storage is empty, a backup heat generator, e.g., an electric or natural gas boiler, is used to supply the residual heat demand. Figure 13 shows the fraction of the residual heat demand ($f_{residual}$) as a function of the dimensioning of the HP, the location as well as the annual and daily load profile types. The capacity ratio (cr) is used as a standardized parameter to describe the dimensioning of the HP.

$$cr = \frac{\dot{Q}_{HP}}{\dot{Q}_{demand,max}}$$

cr	capacity ratio
$\dot{Q}_{HP}$	heating capacity of the HP in kWh/h
$\dot{Q}_{demand,max}$	maximum hourly heat demand during a year in kWh/h

Due to the lower solar fractions in Bern, the residual fraction for the same cr is about 10 % to 20 % higher in Bern compared to both other locations. For each location, the differences between the different load profile types amount to a maximum of about 15 %. However, a cr of 0.5 is sufficient to limit the $f_{residual}$ to a maximum of 10 % in any case. This means that an HP sizing that equals half of the maximum annual heat demand is enough to supply

90 % of the heat demand with one of the two renewable heat generators. Further investigations revealed that the latter is also true for HP systems without a SHIP plant.

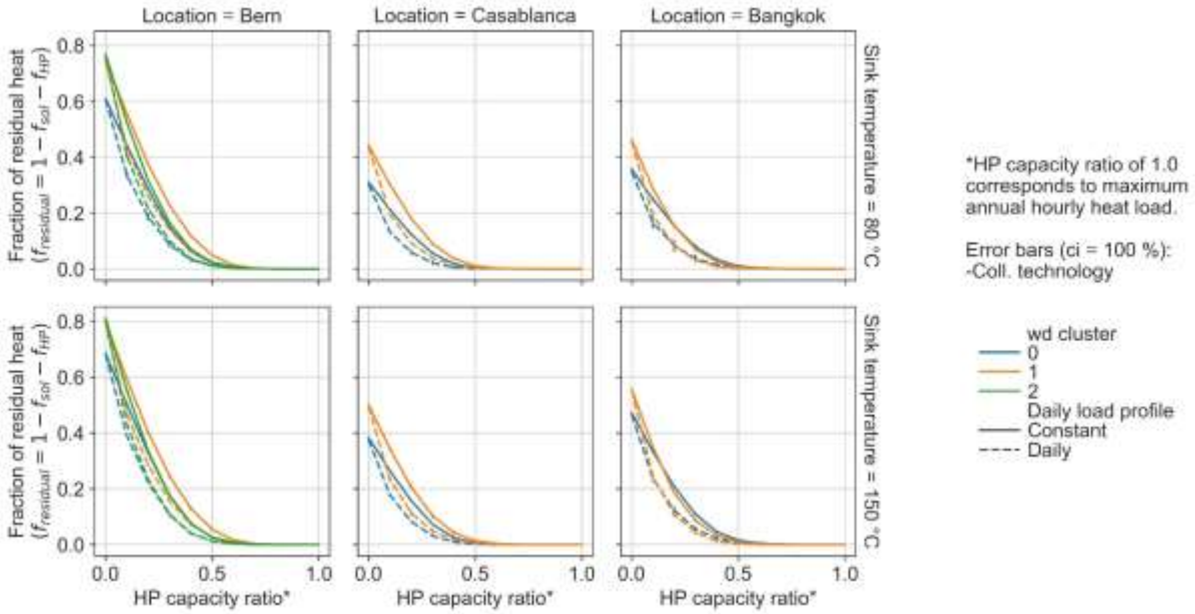

Figure 13: $f_{residual}$ as a function of the location, the capacity ratio of the HP, the annual load profile type (wd cluster) and the daily load profile type.

6 Conclusion and Outlook

It is accepted state of the art to design solar thermal projects with respect to the summer heat demand, which leads to only relatively small solar fractions. “Oversizing” of the solar plant would allow for a relevant increase of achievable solar fractions.

Task 64/IV revealed that research on combined SHIP and HP systems in industry is mostly limited to the outcomes of the Austrian ENPRO project. For individual design of SHIP plants, the VDI 3988 guideline is widely established and can also be used for the design of the SHIP plant in combined SHIP and HP systems since the solar heat should always be prioritized in combined systems to reduce energy consumption and greenhouse gas emissions to the maximum extent. For the combination of both heat generators and even for individual HPs in industry, an established design guideline is missing so far.

The research done in Task64/IV included a simulation study investigating the performance of combined SHIP and HP systems for applications worldwide. If the free space for installing the collectors is not limited, solar fractions of a design according to the VDI 3988 are ranging between 20 % to 40 % for tempered and a minimum of 50 % for sub-tropical and tropical climates.

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